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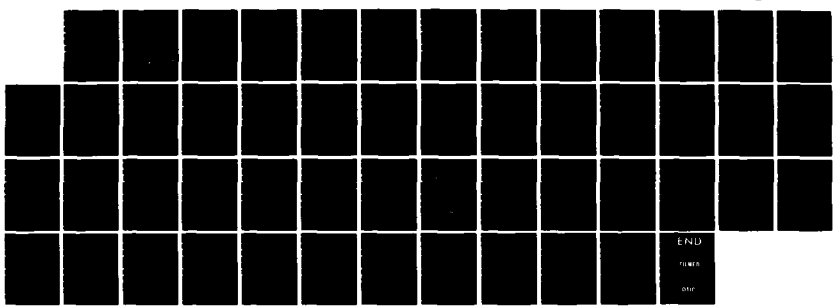

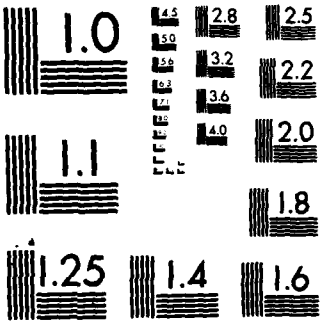

NRL Memorandum Report 5649

Patchiness of Small-Scale Temperature Fluctuations in the Seasonal Thermocline: Results Using a Preliminary Patch Processor Algorithm

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Washington, DC 20363

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Washington, D.C.

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An algorithm is documented which is useful for visualizing patches of fine-scale activity in the upper ocean. It also gives estimates of elementary patch statistics. The algorithm is applied to a ~55 km by ~30 m section of temperature data obtained with a towed array of thermistors in the seasonal thermocline in the Sargasso Sea in late summer. Activity on horizontal wavelengths of 1 to 10 meters is shown to be intermittent, with the size of energetic patches being tens of meters to order one kilometer long and 0.5 to 10 meters high. The length-to-height ratio, on the average, is greater than 100, approaching the ratio of the buoyancy to the inertial frequency. Also, the rms amplitude of the fluctuations in the patches is, on the average, independent of patch size.

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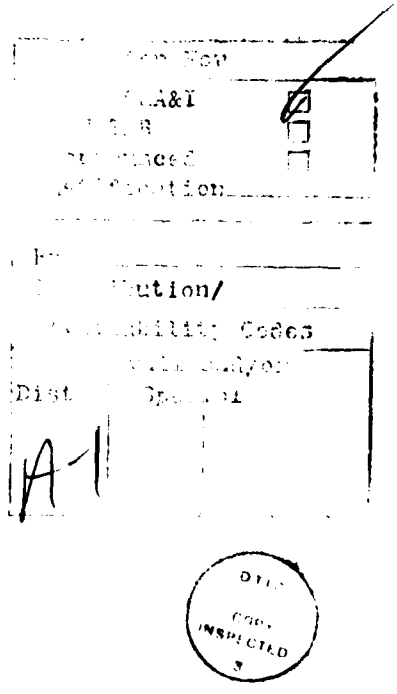


PATCHINESS OF SMALL-SCALE TEMPERATURE FLUCTUATIONS IN THE SEASONAL THERMOCLINE: RESULTS USING A PRELIMINARY PATCH PROCESSOR ALGORITHM

1. Introduction

Fluctuations in the temperature structure of the ocean on scales of centimeters to kilometers are of interest to the oceanographer because they provide information on the physical processes which occur there. They also are of interest to the Navy systems analyst because they affect the performance of undersea systems. Improved knowledge of the spatial and temporal distribution of these fluctuations will increase our understanding of ocean physics and our predictive capability for the performance of present and future undersea systems.

The specific classes of processes of interest here are the finestructure and microstructure which appear in small-scale and very small-scale measurements, respectively. Most observations of these fluctuations of temperature in the thermocline have been made with vertically profiling instruments which often are sensitive enough to resolve the dissipation scale. There have been a more limited number of observations which have been made in the horizontal and by moving the instrument up and down while moving horizontally (a so-called tow-yo) to get an estimate of horizontal and vertical scales simultaneously. This has yielded estimates of the two-dimensional character of the small-scale structure, and there is a proclivity for the microstructure to be very patchy and for these patches to be quite elongated in the horizontal. These tow-yo observations have been made with instruments on a controlled fish, so they remain essentially one-dimensional.

Manuscript approved June 28, 1985.

Gibson (1982) has raised an issue with the vertical profiler microstructure observations which has to do with sample statistics. It is argued that only a small number of vertical profiles are obtained and, because of the non-Gaussian statistics of the dissipation events (a small number of very energetic events), these energetic events are likely to be missed and, as a result, the estimates of dissipation in the ocean badly underestimated. A counter argument is that the horizontal tows, on the other hand, have to be extremely long because of the large horizontal-to-vertical anisotropy in patch shape. If the ratio of horizontal to vertical size of the patches is 100:1 for instance, the total length of tow would have to be the order of 100 times the total length of drop data in order that the number of observed events be comparable.

These difficulties can be eliminated by towing an array of instruments, so that a two-dimensional section of the ocean is observed. There is, however, a concomitant disadvantage of the array technique in that the instruments in the array generally must be much simpler than those used in a towed fish or dropped profiler. The central issue of the towed sensors is whether or not the frequency response or, rather, the spatial resolution, is adequate to measure the fluctuations. The usual sensors on towed arrays are thermistors which respond to horizontal temperature fluctuations on scales of about 0.5 m or larger at nominal tow speeds. This clearly is not adequate to resolve the microscale, but it is adequate to detect patches of finescale activity in which the microstructure may be embedded. The relationship between the microstructure and the finestructure is set aside for the present, and the thermistor array data are used directly to characterize the finescale activity. The sensor, data acquisition, and preliminary processing systems are discussed in Morris et al (1983).

In this paper, the data processor used to exhibit the patchy nature of the fluctuations is documented. The description is more complete than previously given in sketchy form by Okawa and Dugan (1981), Dugan and Okawa (1983), and Dugan (1984). Then, the spatial distribution of temperature fluctuations is explored in some detail with observations obtained with the towed array in a summertime thermocline. Patches of energy in the 1-10 meter horizontal wavelength band are described and horizontal-to-vertical aspect ratios are determined.

A temperature contour plot derived from the full 90 m (180 sensor) vertical aperture of the chain is shown in Fig. 1.1. It is clear that the observations were made in a frontal zone, and just how this will affect the generality of the results is not known.

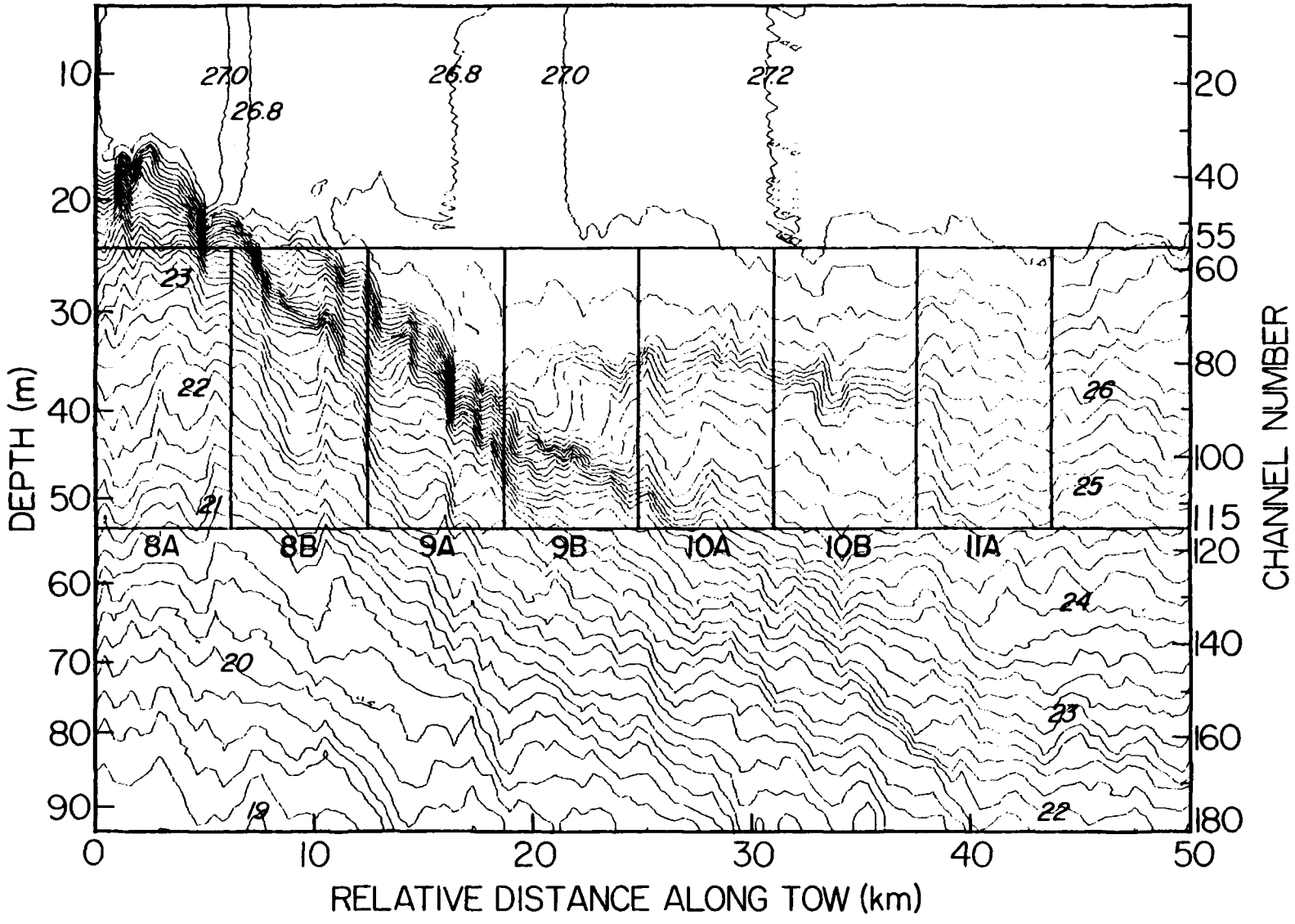


Fig. 1.1 Temperature contours at 0.20 °C intervals beginning at 0429 GMT, 20 July 1981 and continuing for 320 minutes. In space, this section represents about 50 km. The data examined in this report are from the boxes labelled 8A, ..., 11A.

2. Description of Algorithm

A block diagram of the data processor is given in Figure 2.1. The original data were recorded at 20 Hz and then 5-point averaged and subsampled to 4 Hz. This roughly is comparable to the vertical spacing of sensors which nominally is 50 cm. The data from each thermistor are high-pass filtered to eliminate scales longer than 10 m, and the rms fluctuations are obtained in contiguous, but independent, bins, each about 70 m long. This yields a two-dimensional array of fluctuation level in the 1-10 m band having resolution of about 0.5 m by 70 m.

The data examined here are from sensors 55-115 (excluding 72), only. The period shown in Fig. 1.1 corresponds to TEMDAT tapes 8, 9, 10, and 11 for the 1981 TT6 (Tow Test 6) run. Each tape is 80 min long, so 320 min of data are shown. For analysis convenience, each tape is divided in half, giving 8 sections--8A, 8B, 9A, 9B, 10A, 10B, 11A, and 11B--each 40 min long by 60 sensors high. Section 8A is examined in detail in this section; then, in Section 3, the most significant results are shown for 8A, ..., 11A. Results from 11B have been inadvertently lost. (These calculations were done in 1982 and could not be conveniently duplicated. As it happens, Section 11B was of little significance in terms of patch content.)

The physical size of each section is as follows. The average sensor spacing in the range examined is 48 cm, so the vertical extent is about 30 m, from about 24 to 53 m in depth. Results are plotted with a y-axis linear in channel number. (The reader is cautioned to ignore any annotation on the y-axis that differs from these values.) Ship speed relative to the depth of about 50 m was 2.87 m s^{-1} over the period of interest. This gives 55.1 km for the amount of water horizontally sampled. Each half tape, then,

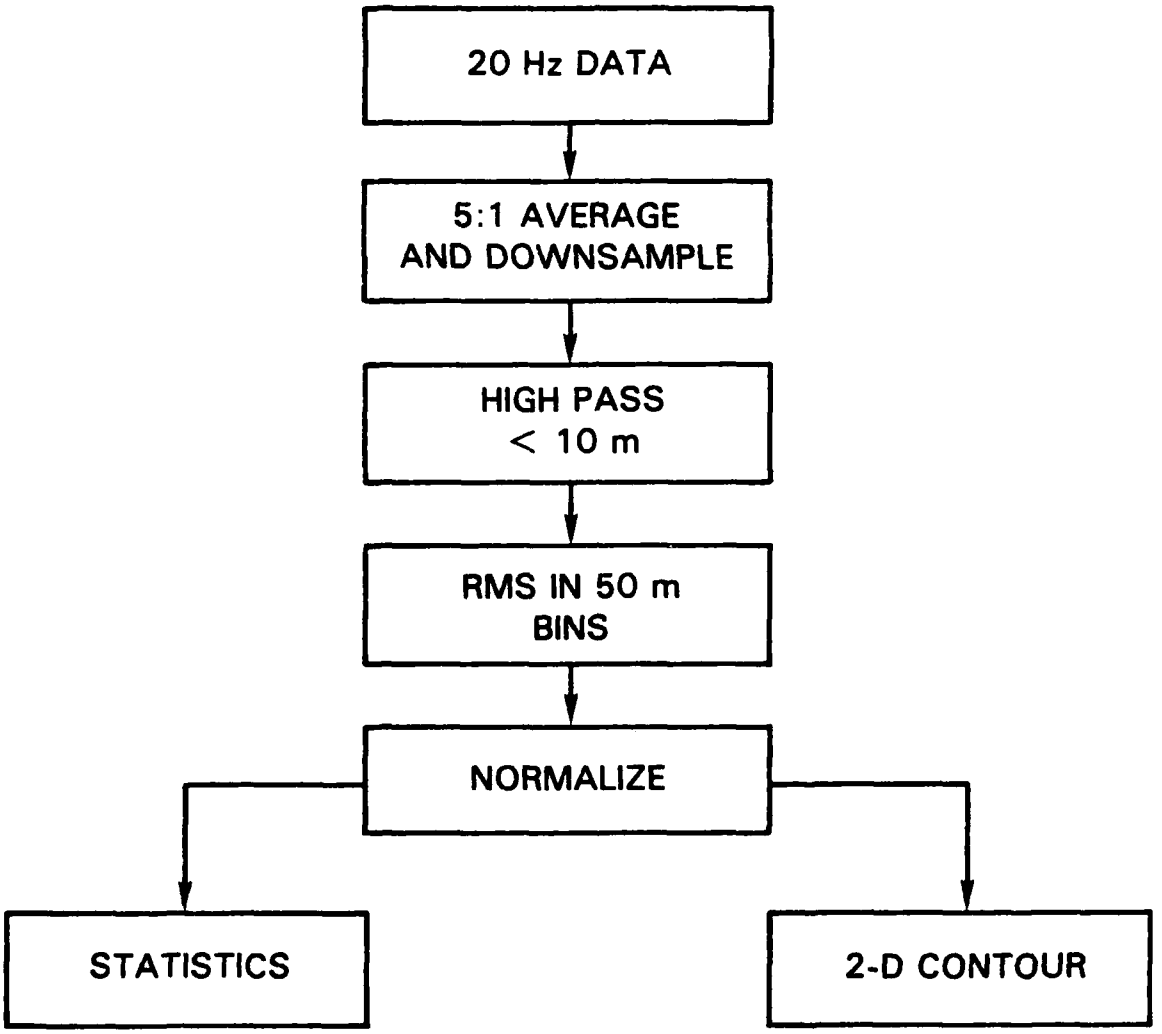

20 Hz DATA
5:1 AVERAGE AND DOWNSAMPLE
HIGH PASS < 10 m
RMS IN 50 m BINS
NORMALIZE
STATISTICS
2-D CONTOUR

Figure 2.1

corresponds to 6.88 km (hereafter, 7 km) of sampled water. Each half tape was further divided into 100 "chunks". Thus, each section of ocean examined contains 6,000 elementary rectangles, each about 70 m by 50 cm in extent.

The vertical temperature profile for the 7 km section denoted 8A is shown in Fig. 2.2. Each data point is the mean value for a given thermistor. The profile is not very smooth as a result of inter-sensor calibration errors; thus, local vertical gradients of the mean (Fig. 2.3) show a significant amount of scatter. Because of this scatter, the gradient values were not used to normalize the magnitude of the rms fluuctuations. Instead, the mean value of the rms level on each sensor is used to normalize the fluctuation levels. This normalization also accommodates the possibility that some of the sensors are more responsive to the high-frequency fluctuations than others, either because of gain miscalibrations or unmatched frequency response of the probes. This normalization is accomplished by dividing the rms levels of each thermistor by the mean (of the 100 samples) of the rms level for that sensor. These normalized rms values have been termed the residue values.

A histogram of these normalized values is shown in Fig. 2.4. It is important to note that this probability density function has a long tail at the higher energy end. If the original temperature fluctuations were normally distributed, the pdf of variance values would be Rayleigh distributed. This distribution, and that of the rms values, has an exponentially decreasing tail which decays much faster than that exhibited in Fig. 2.4. In fact, this distribution clearly is more nearly described as log-normal (Dugan, 1984).

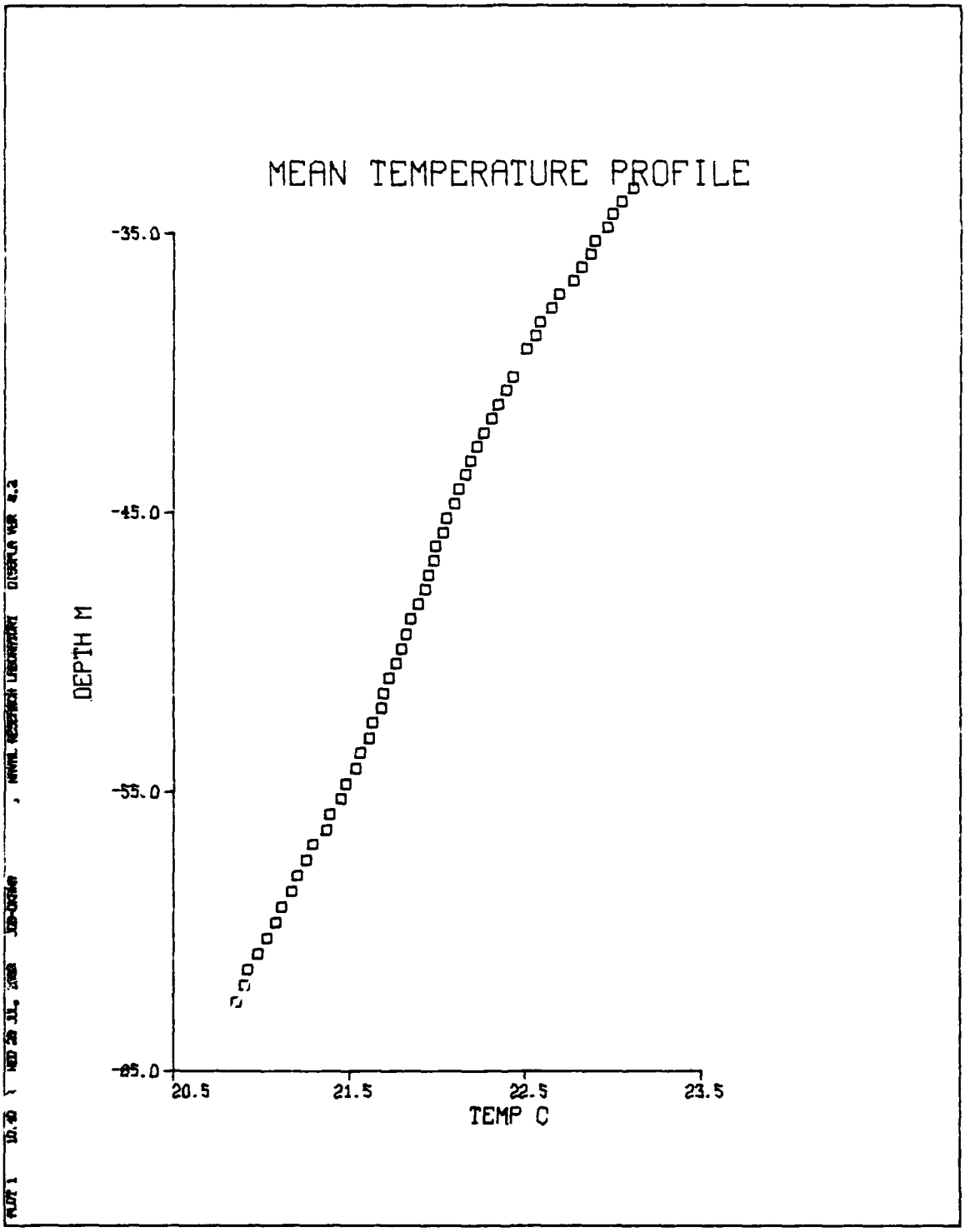

MEAN TEMPERATURE PROFILE
-35.0
-45.0
-55.0
-65.0
DEPTH M
20.5
21.5
22.5
23.5
TEMP C

Figure 2.2

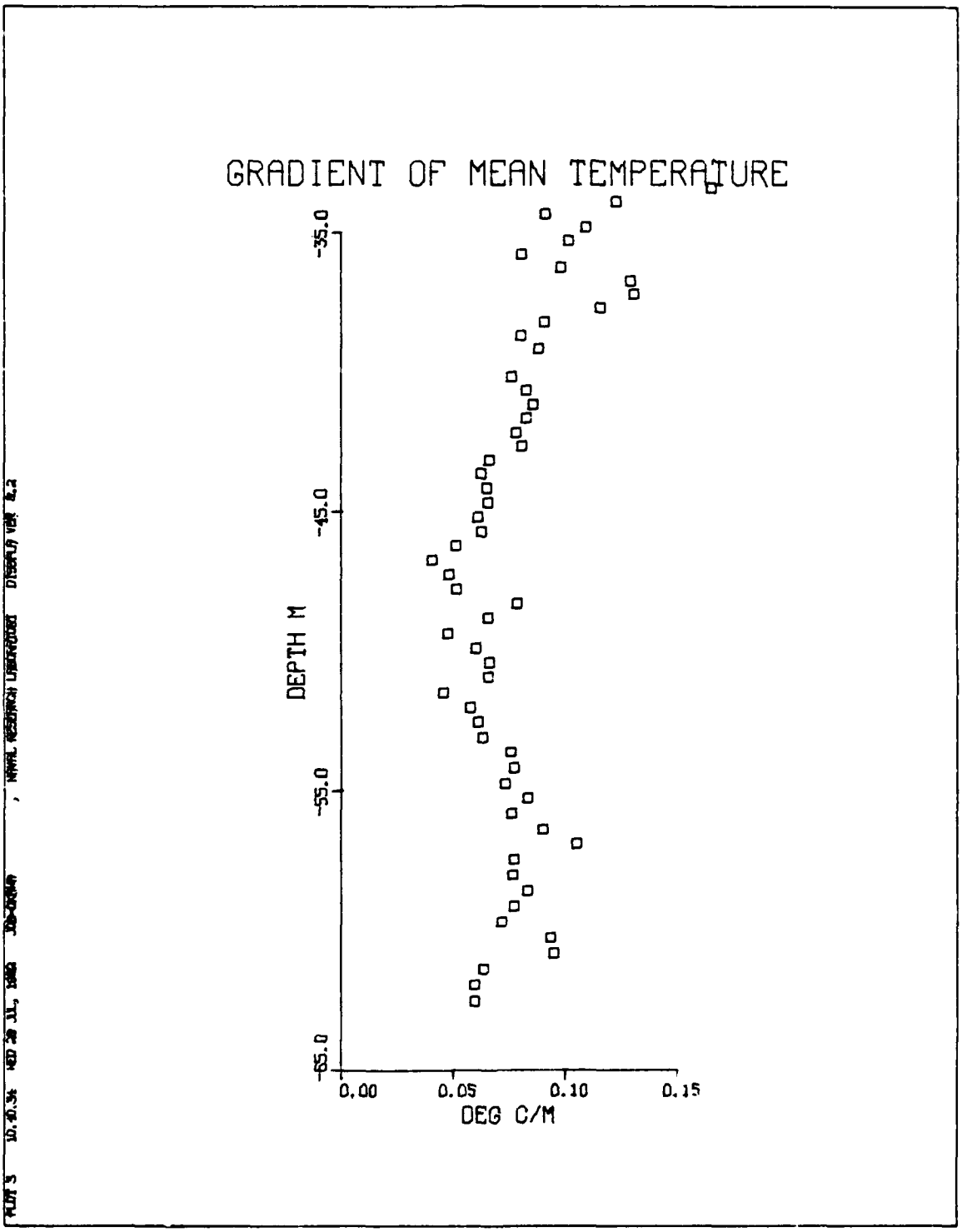
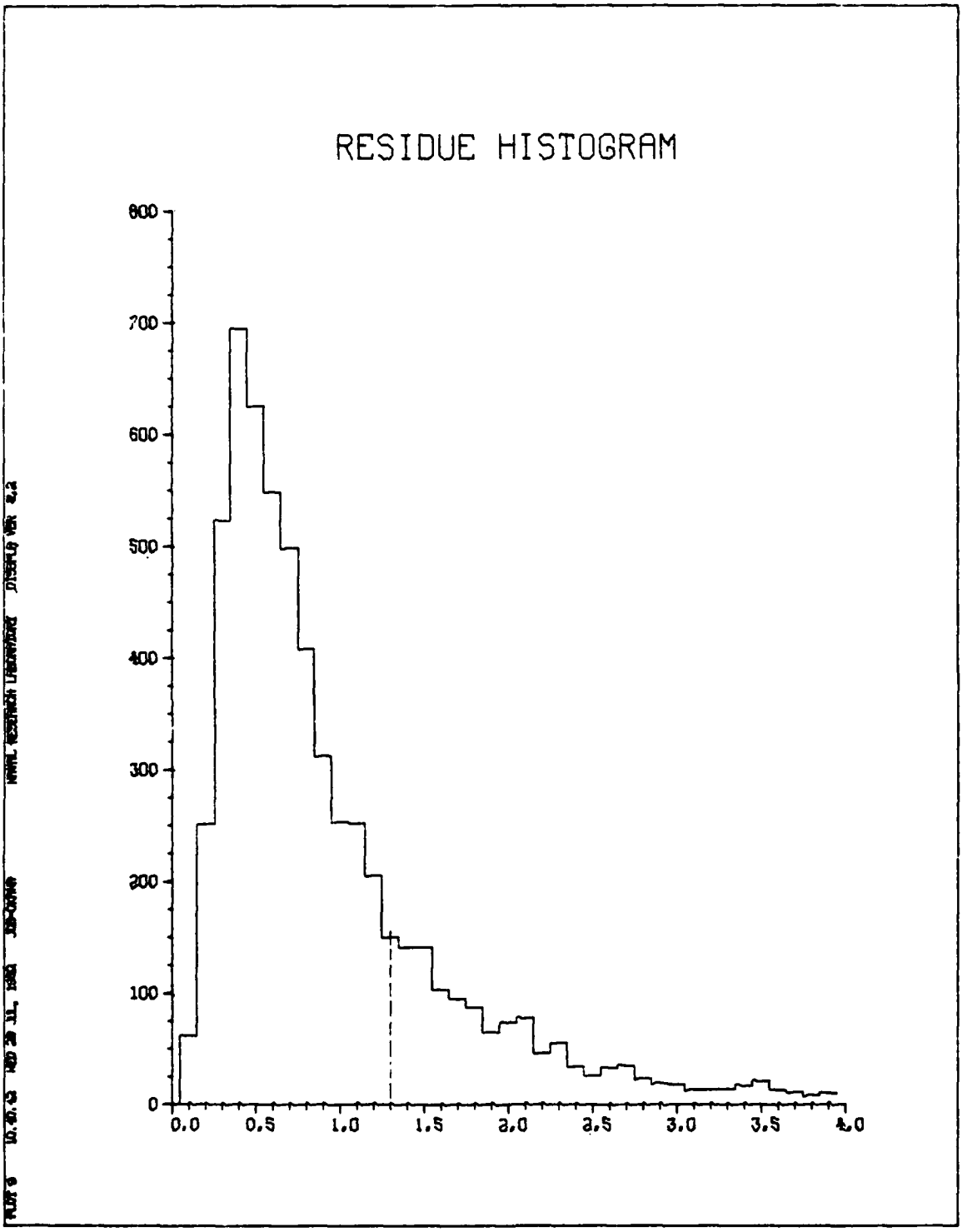

GRADIENT OF MEAN TEMPERATURE
DEPTH M
-35.0
-45.0
-55.0
-65.0
0.00
0.05
0.10
0.15
DEG C/M

Figure 2.3


RESIDUE HISTOGRAM
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700
600
500
400
300
200
100
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0

Figure 2.4

The profile of the rms values is exhibited in Figure 2.5. The scatter in this profile gives an idea of the variability in the amount of normalization to which the rms data are subjected. The noise level of the measurements is equivalent to a 15-bit digitizer acting over a 20 °C range; thus, the rms noise level is about 2×10^{-4} °C, well below the rms residues shown.

Figure 2.6 is the rms level for each thermistor of the average temperatures in the 70 m bins. This profile represents variability in 130 m and longer scales produced by a modulation of the layered finestructure by vertically coherent motion. This conclusion comes from the observation that the level is largest near the upper and lower parts of the profile where the vertical temperature gradient is largest. When internal waves modulate the local vertical locations of water parcels, the resulting rms temperature fluctuations in this band are proportional to the local vertical temperature gradient. Thus, the general shape of Fig. 2.6 is similar to that of Fig. 2.3. In addition, the smoothness of the profile in Fig. 2.6 leads to the conclusion that the gain calibrations on the individual sensors were quite accurate; thus, the scatter in the mean rms levels was due to differences in sensor bandwidth.

After calculation of the two-dimensional array of normalized rms values, these data are processed on divergent paths as exhibited in Fig. 2.1. On one path, the values of the 60 x 100 point array are plotted on a contour diagram. This process requires no explanation, so we will proceed with the details of the other path.

The locations of the data having large rms values turn out to be quite clustered in depth-range space. That is, the majority of the energetic points are clustered in a relatively small part of the two-dimensional section.

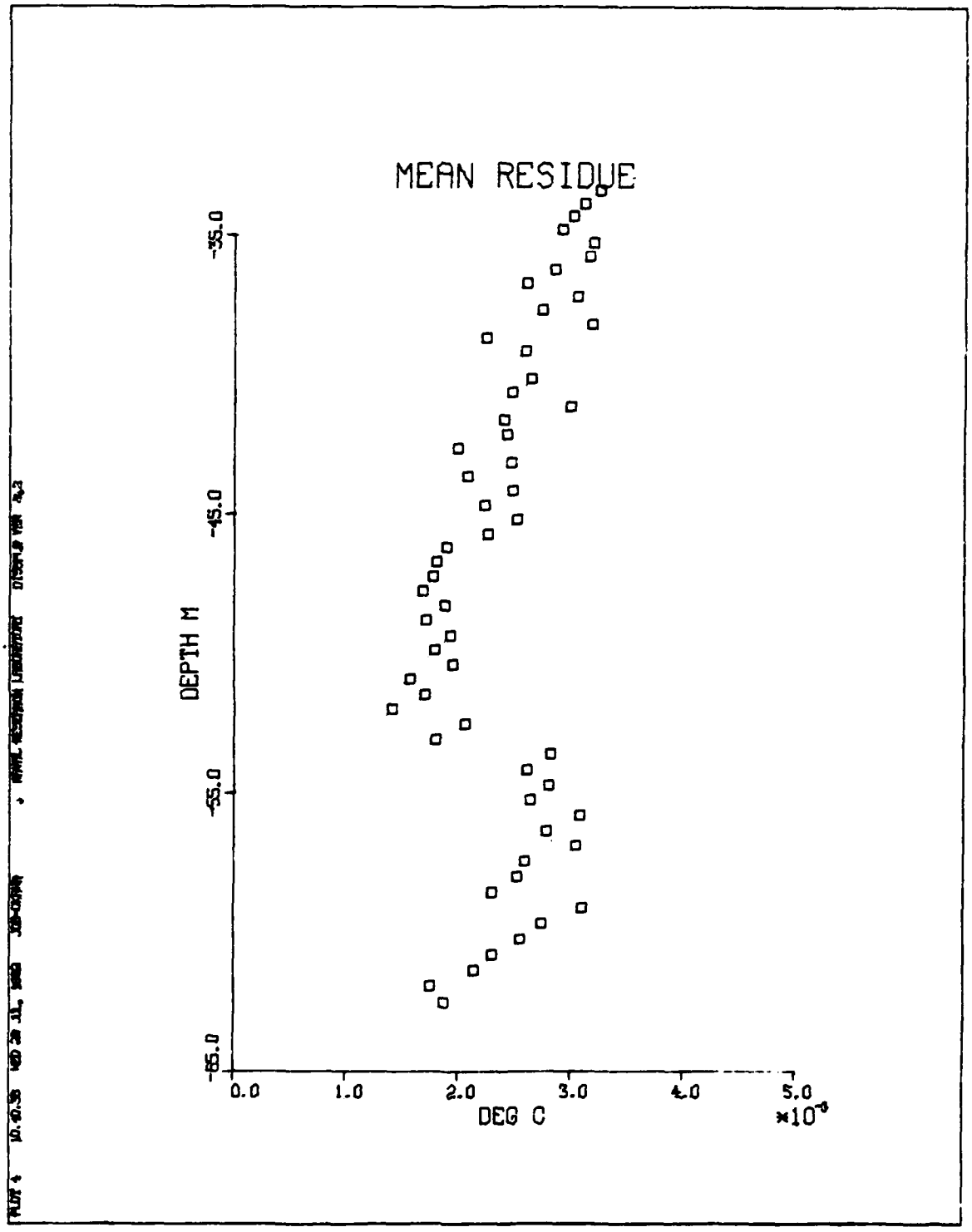


Figure 2.5

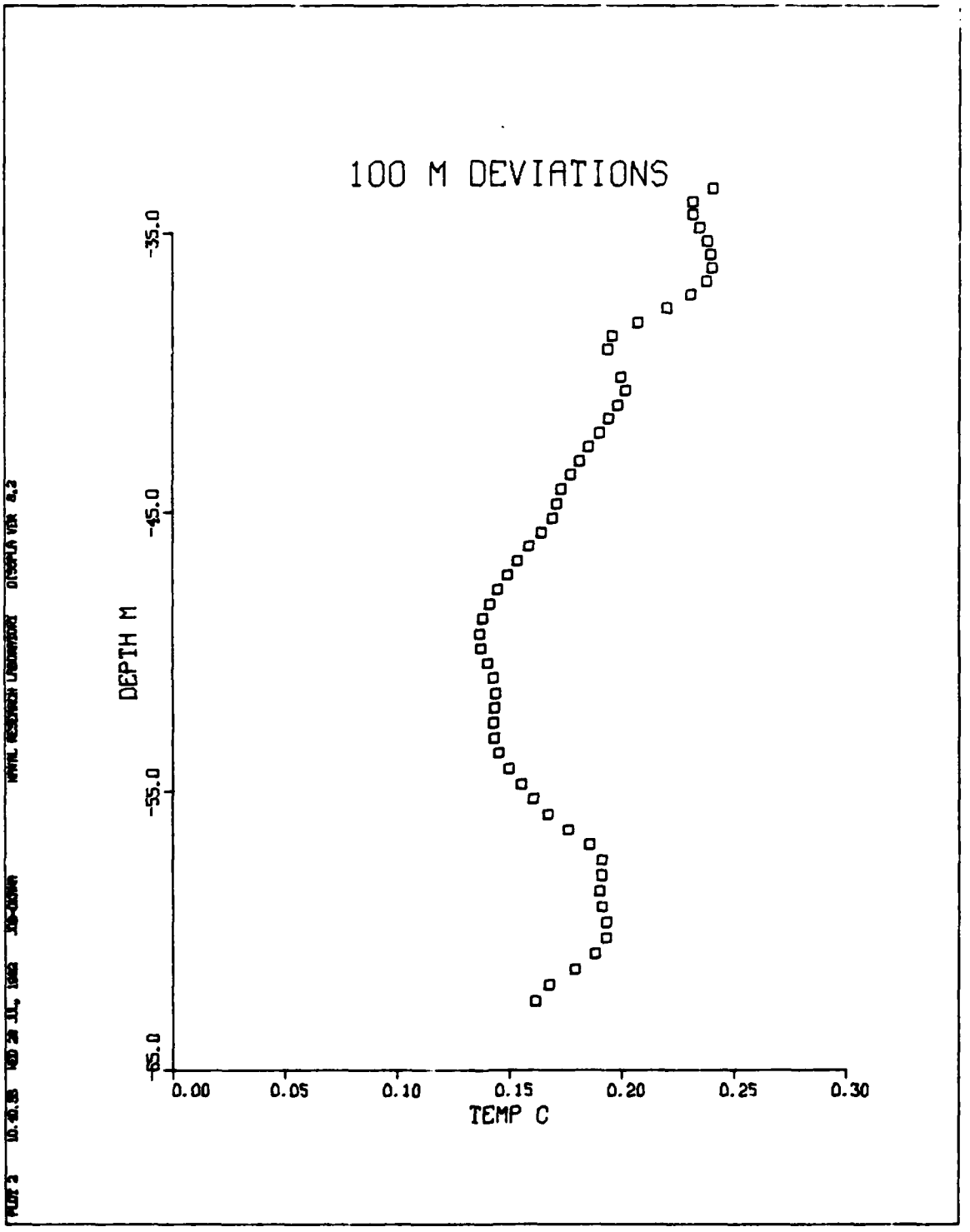

100 M DEVIATIONS
-35.0
-45.0
-55.0
-65.0
DEPTH M
0.00
0.05
0.10
0.15
0.20
0.25
0.30
TEMP C

Figure 2.6

In the histogram in Fig. 2.4, for example, the points with values more than 1.3 times the mean rms value occur about 15% of the time (i.e., about 15% of the area in the depth-range section shown). Yet, the vast majority of these 900 data points (i.e., 0.15 x 6000) are agglomerated in just 35 groups. These groups, or "patches", are the events of interest, and their statistics are the concern of the remaining analyses.

The primary parameter calculated in this report is the size and shape of these patches. This is a difficult task since a patch often is irregular in shape and its energy level varies considerably as a function of position in its cross-section. In addition, the patch parameters are a function of the threshold level above the mean rms level, with the size shrinking with increasing threshold. For example, a patch having two centers of high energy will be exhibited as two separate, smaller patches if the threshold is raised high enough. Nevetheless, a given threshold is chosen and then the size is calculated.

The calculation of size is accomplished with an additional simplification. The patch is characterized as having a unique width and height, and each of these is assumed to be equal to twice the square root of the second moment of the rms levels about their centroid. The centroid is computed to be the center of all points in the patch, weighted by the rms level of each point, That is,

$$\langle x \rangle = (1/\sigma_t) \sum_{i=1}^{N} \sigma_i \, x_i \quad ,$$

where $\langle x \rangle$ is the horizontal location of the center, x_i is the horizontal location of each point in the patch, σ_i is the rms value of each point, σ_t is the sum total rms level in the patch, and N is the number of points in the patch. Then, the width is defined by the formula

$$(\text{width}/2)^2 = (1/\sigma_t) \sum_{i=1}^{N} (x_i - \langle x \rangle)^2 \sigma_i .$$

Figure 2.7 is a scatter plot of the half-width and half-height of each of the patches found in this sample. For the data in the figure, the threshold has been chosen to be 1.3 times the mean rms value. The half-widths vary from about 30 m to 350 m and the half heights from about 25 cm to 5 m. (Note, the units on the plot are half-width and half-height, and the scales are units of the elementary rectangle, i.e, 50 cm by 70 m. Thus, the value unity in the vertical is 50 cm and in the horizontal is 70 m.) In physical units, values along the diagonal on this plot imply a horizontal to vertical scale ratio of 143 to 1. The ratio N/f ranges from about 150 to 300.

The final parameter which has been estimated is the distribution of activity level of the patches as a function of patch size. The activity level simply is represented by the sum of the rms levels in a given patch. Fig. 2.8 is the result for the sample case. The horizontal axis is the area in units of the elementary rectangles. The straight line on this plot, which is 1.3 times the diagonal (i.e., the diagonal moved upward 1.3 units on the vertical axis), is the result for no bias of activity level over size of patch. All data points are above this line, as required by the threshold. However, their amplitude above the line is equally distributed among all sizes, and the conclusion is reached that size is not

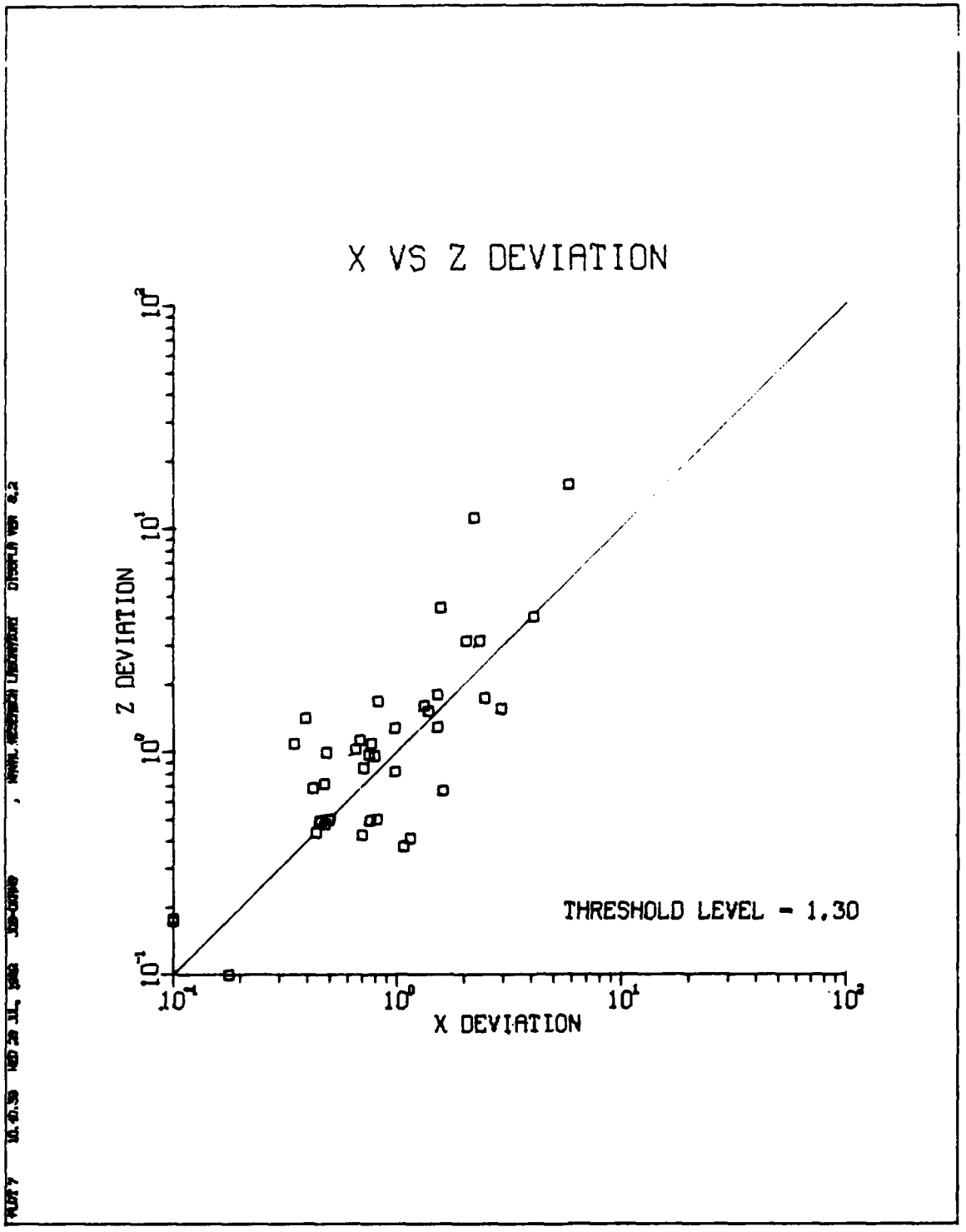

X VS Z DEVIATION
Z DEVIATION
X DEVIATION
THRESHOLD LEVEL = 1.30

Figure 2.7

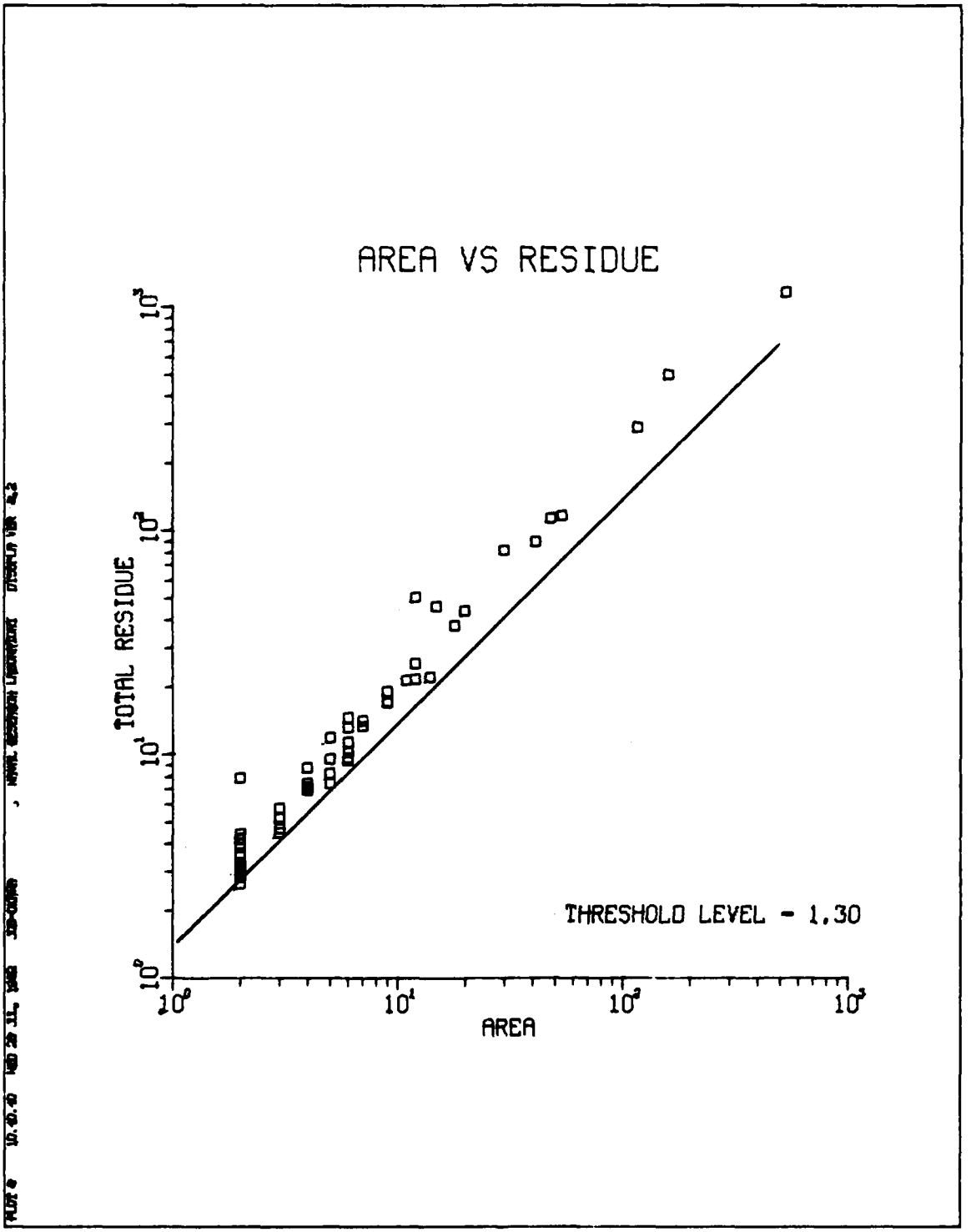


Figure 2.8

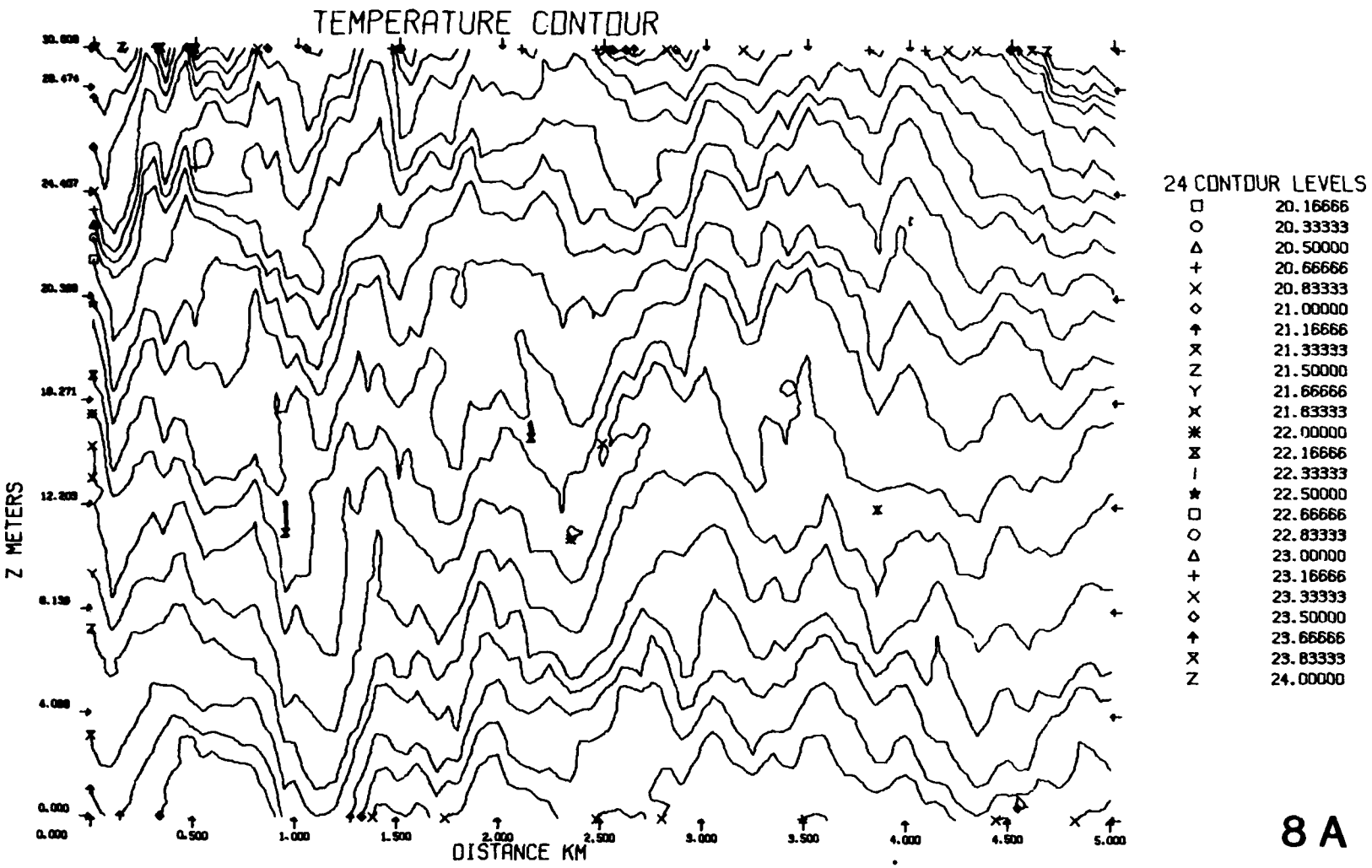
a factor in the activity density level of a patch. That is, large patches are not more energetic on the average than small ones.

3. Results

The patch processor has been applied to the sections of towed temperature data shown in Fig. 1.1: 8A, 8B, 9A, 9B, 10A, 10B, and 11A. Each is represented in the remaining portion of this report by the following plots:

- high resolution temperature contour plot,
- patch contour plot,
- normalized rms level histogram (except 8B), and
- patch size scattergram (except 8B).

In the contour plots, the horizontal extent is nearly 7 km, not 5 km as indicated on the plots.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Z METERS
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1.000
1.500
2.000
2.500
3.000
3.500
4.000
4.500
5.000
24 CONTOUR LEVELS
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20.33333
20.50000
20.66666
20.83333
21.00000
21.16666
21.33333
21.50000
21.66666
21.83333
22.00000
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22.33333
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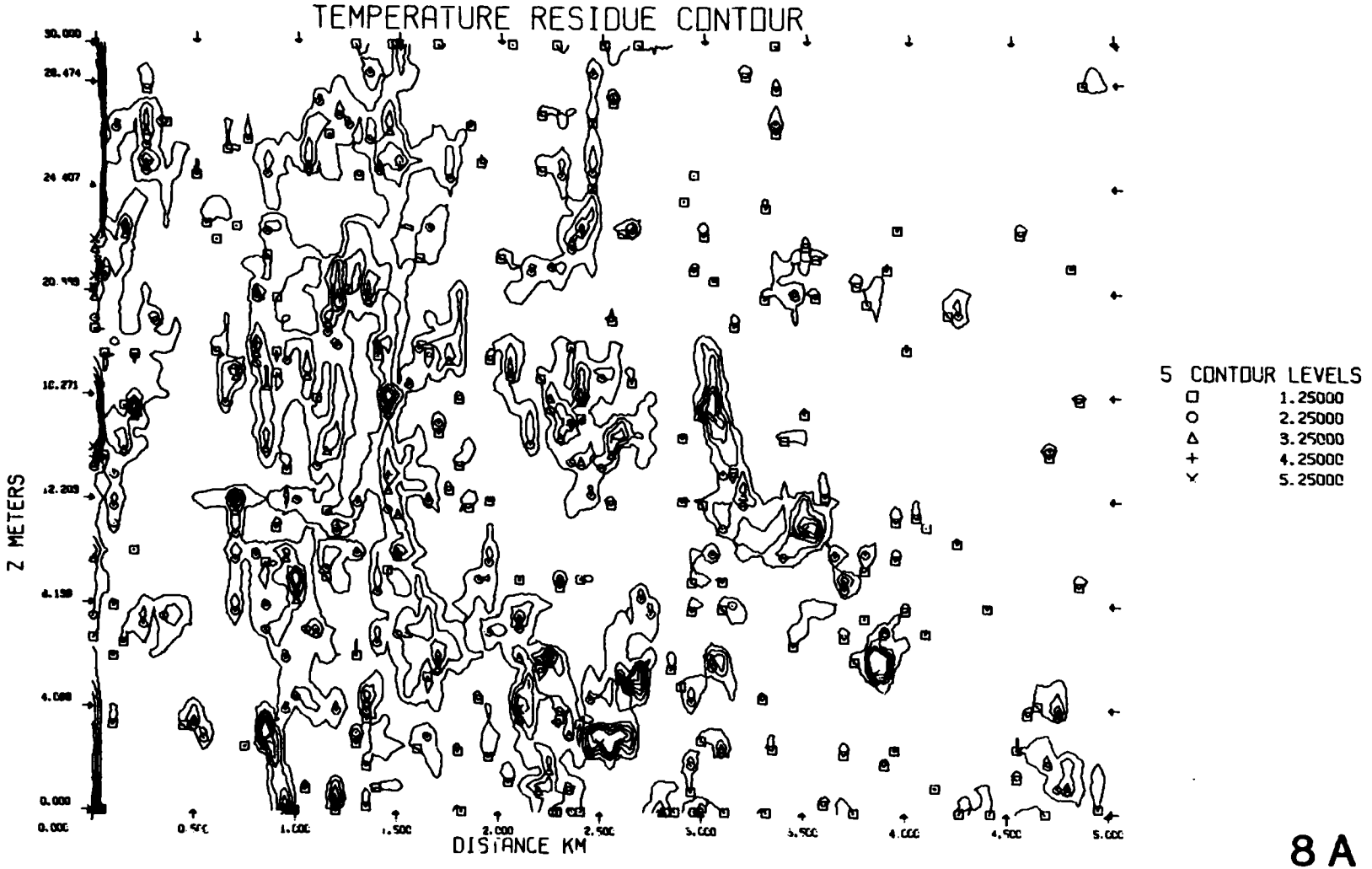
23.83333
24.00000

8 A


TEMPERATURE RESIDUE CONTOUR
Z METERS
DISTANCE KM
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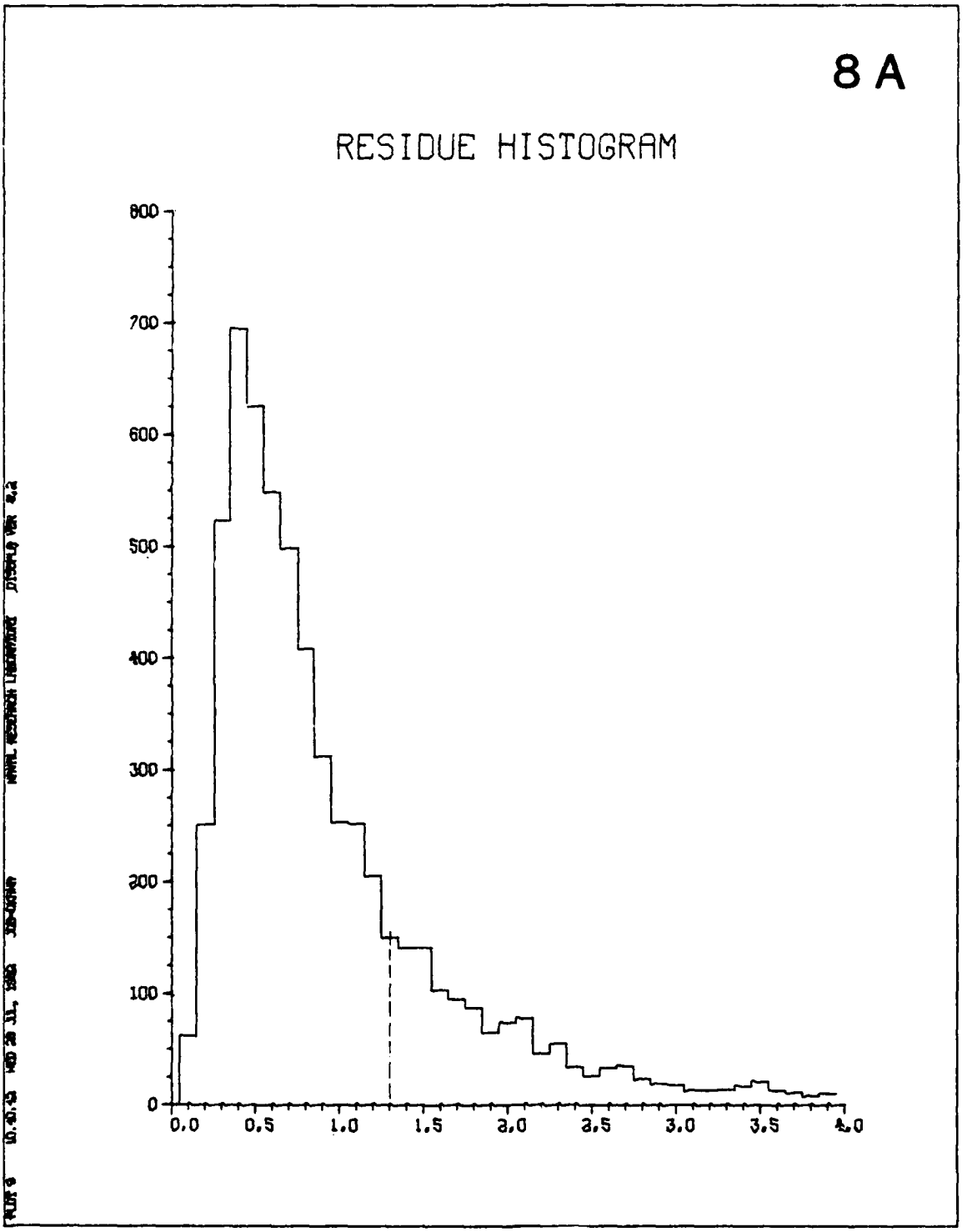
3.25000
4.25000
5.25000

8A

8 A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2.5
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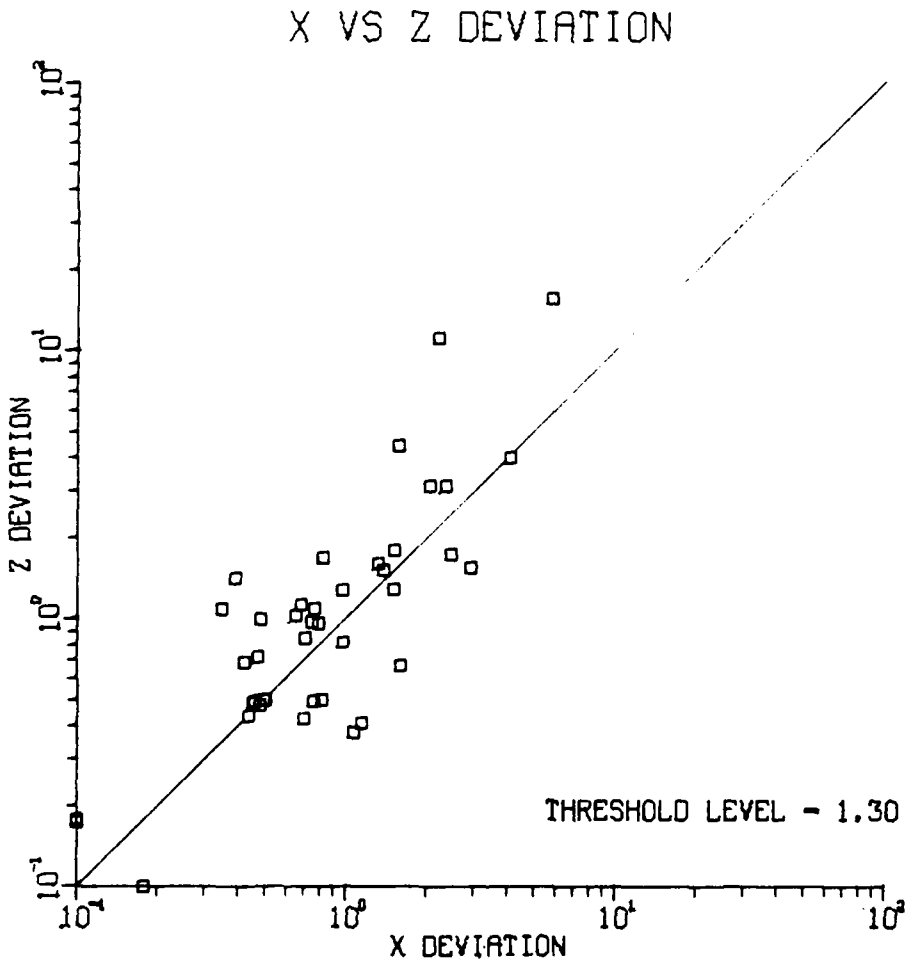
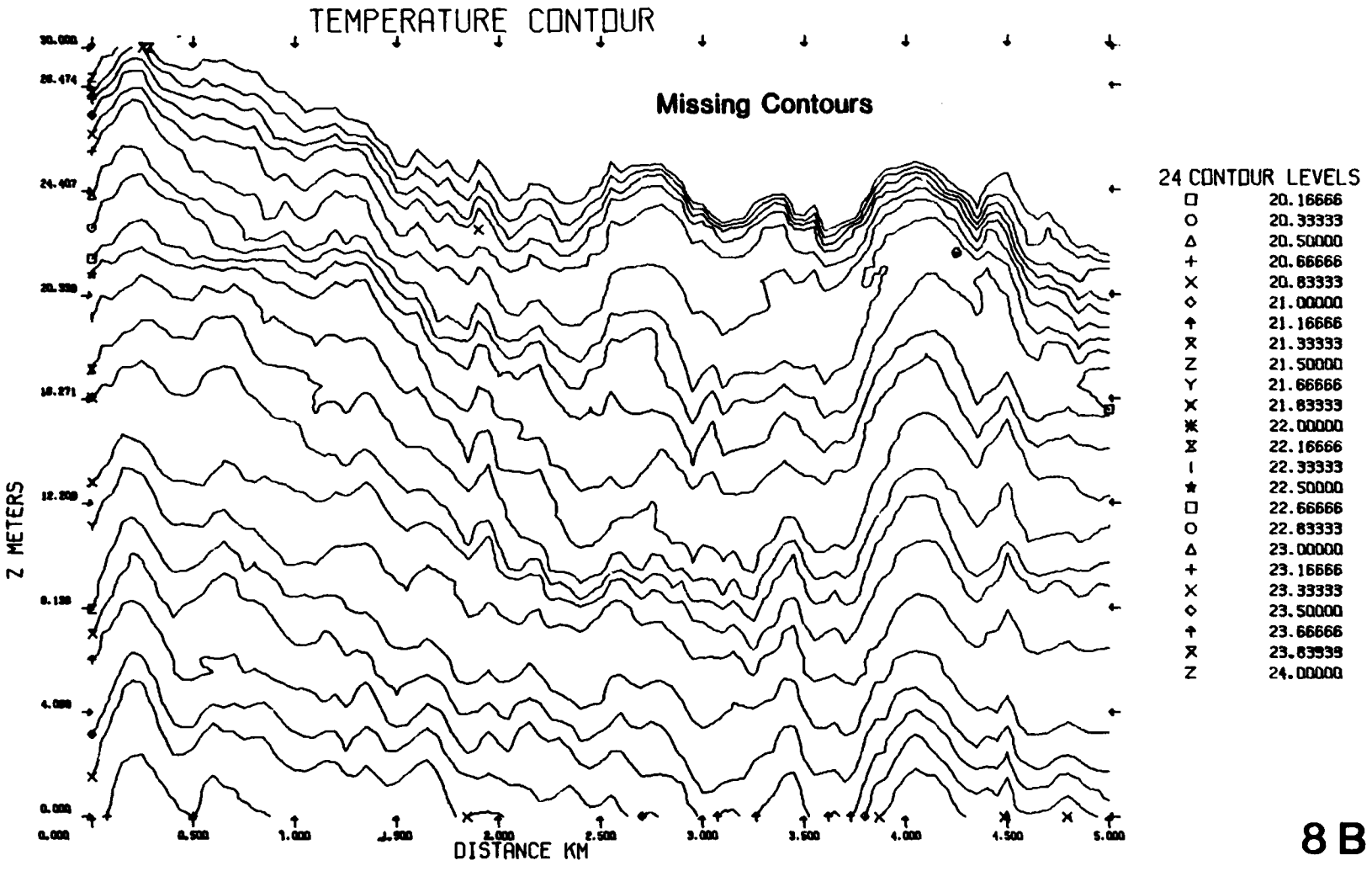
8 A


X VS Z DEVIATION
Z DEVIATION
X DEVIATION
THRESHOLD LEVEL = 1.30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Missing Contours
Z METERS
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1.000
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2.000
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3.000
3.500
4.000
4.500
5.000
24 CONTOUR LEVELS
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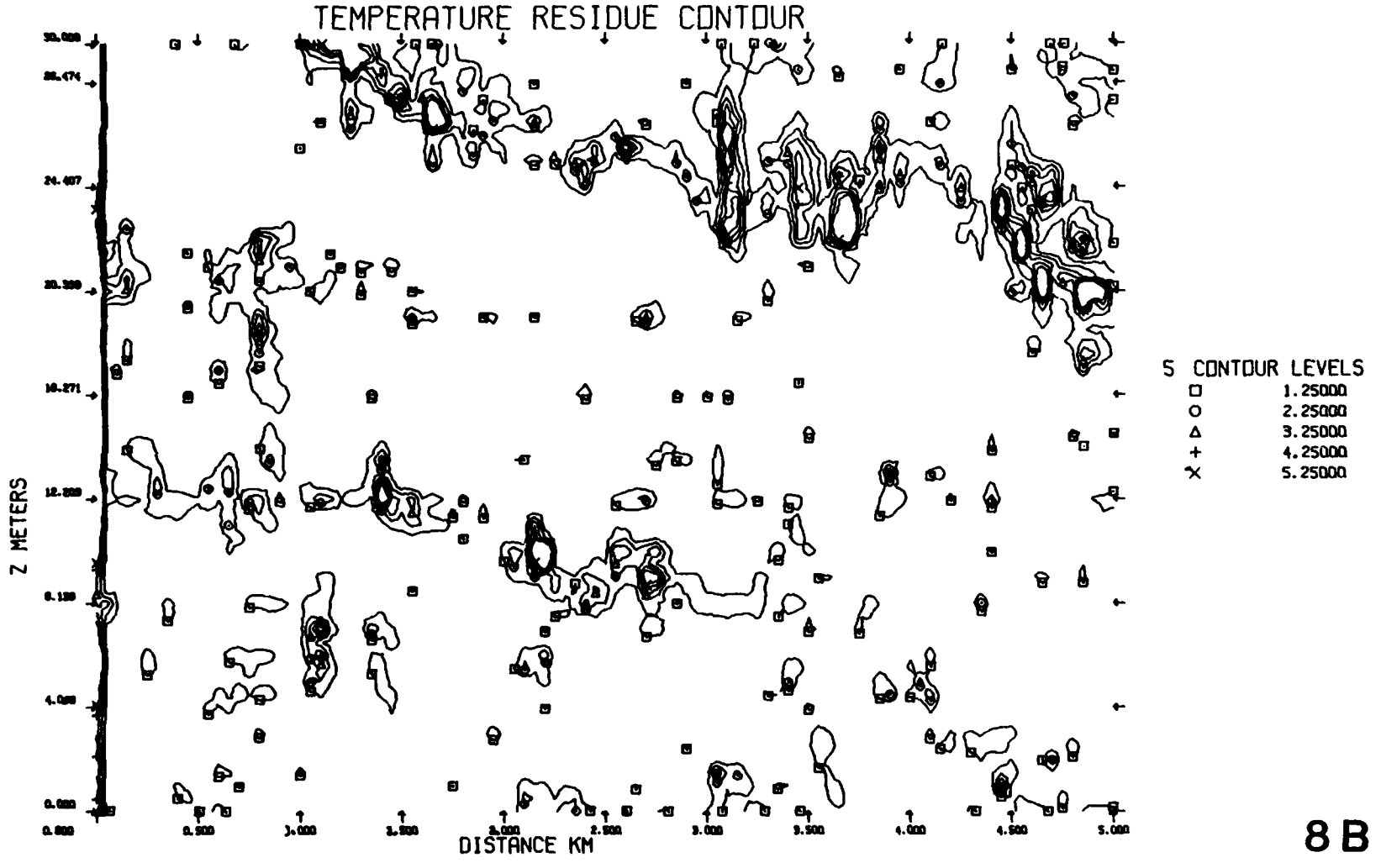
8B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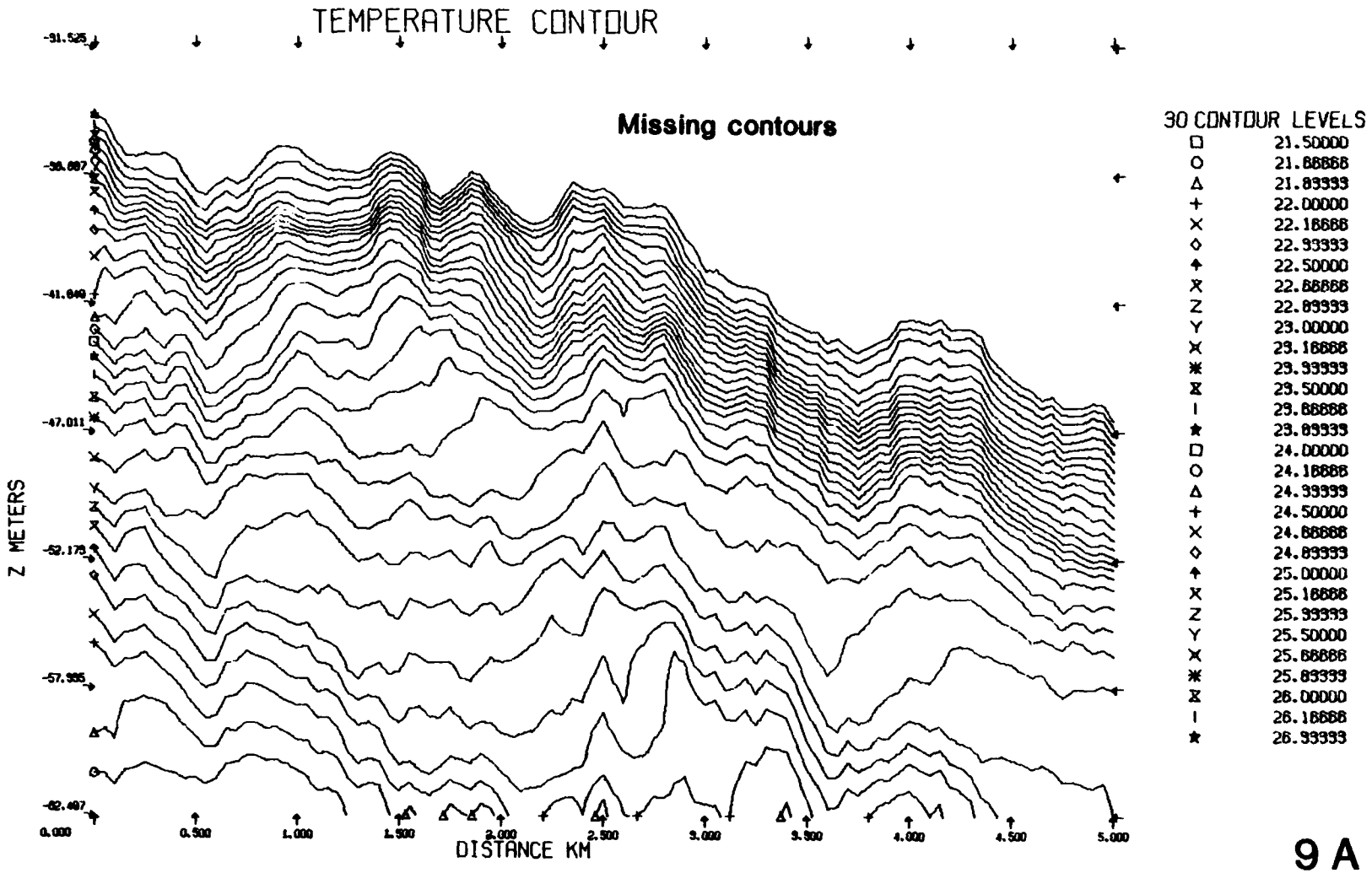
8B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25.16666
25.33333
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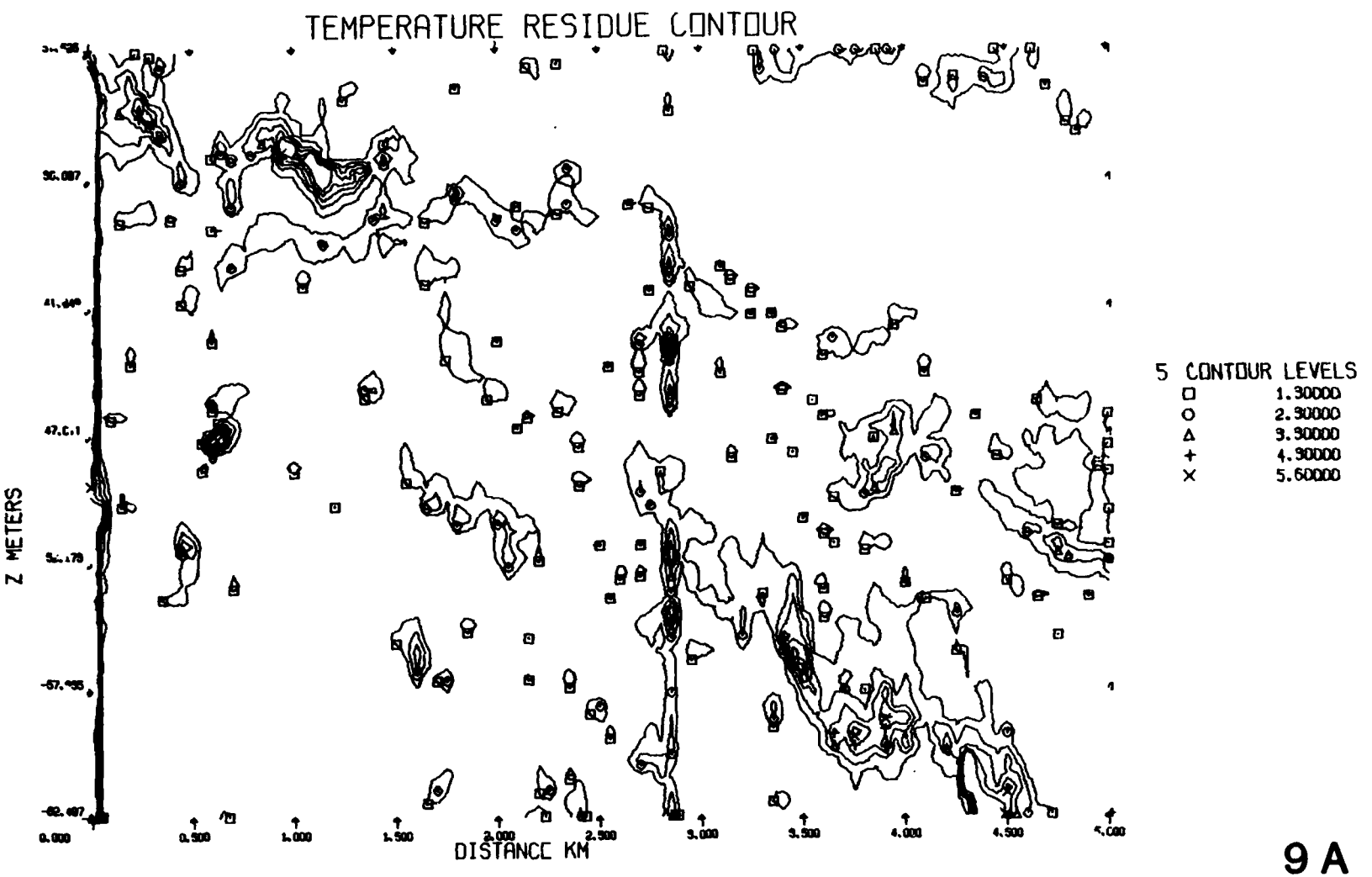
-62.497
0.000
0.500
1.000
1.500
2.000
2.500
3.000
3.500
4.000
4.500
5.000
DISTANCE KM

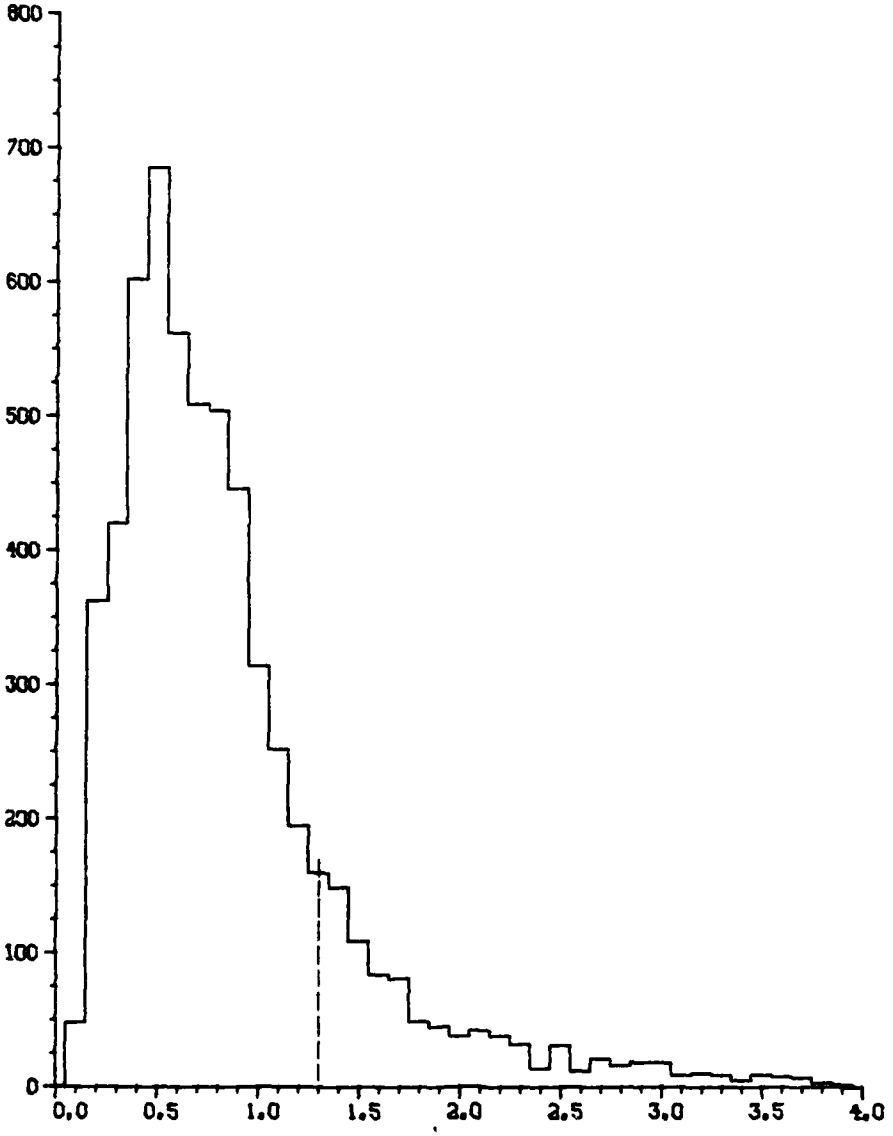
9A


TEMPERATURE RESIDUE CONTOUR
Z METERS
DISTANCE KM
0.000
0.500
1.000
1.500
2.000
2.500
3.000
3.500
4.000
4.500
5.000
5 CONTOUR LEVELS
1.30000
2.30000
3.30000
4.90000
5.60000

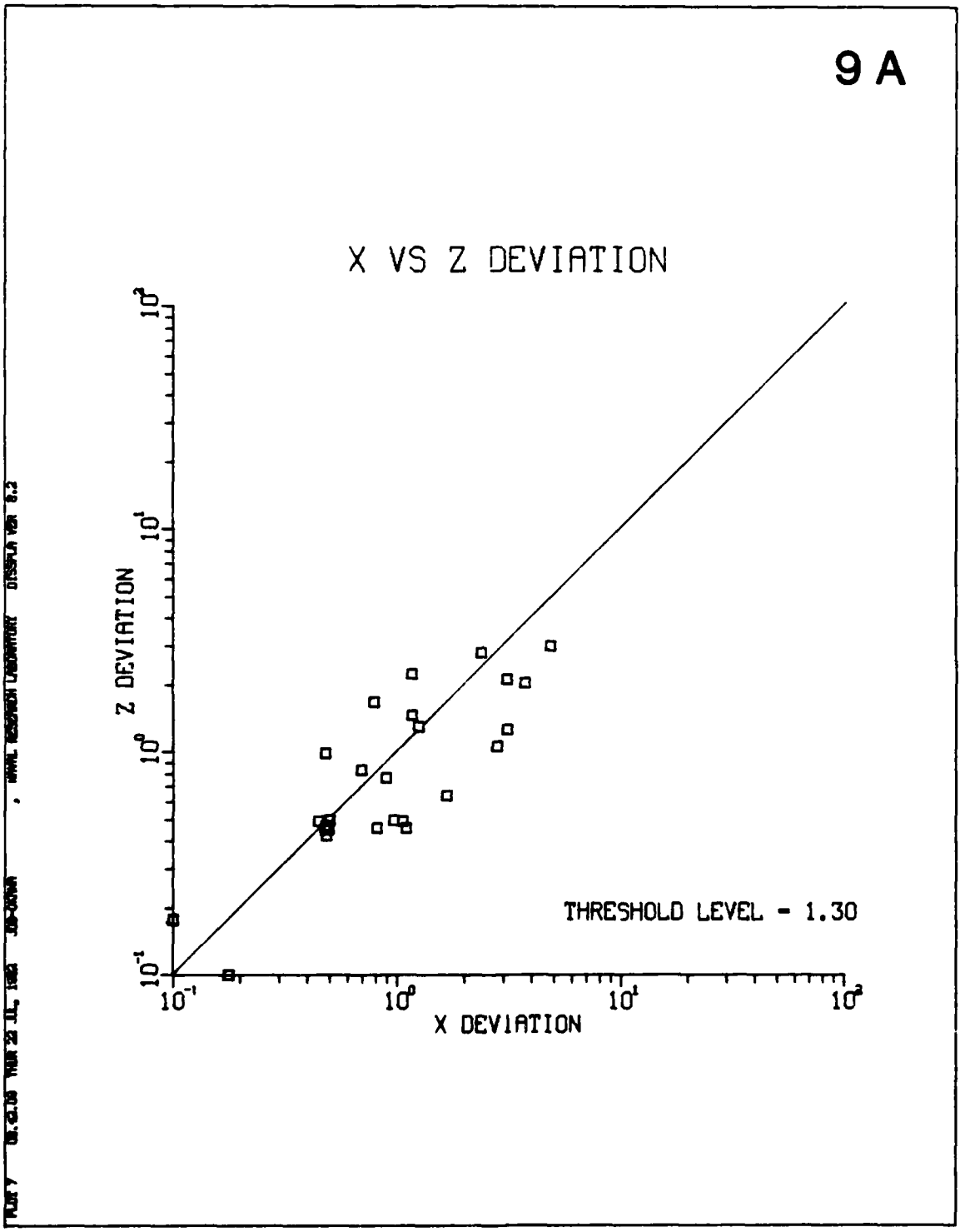
9A

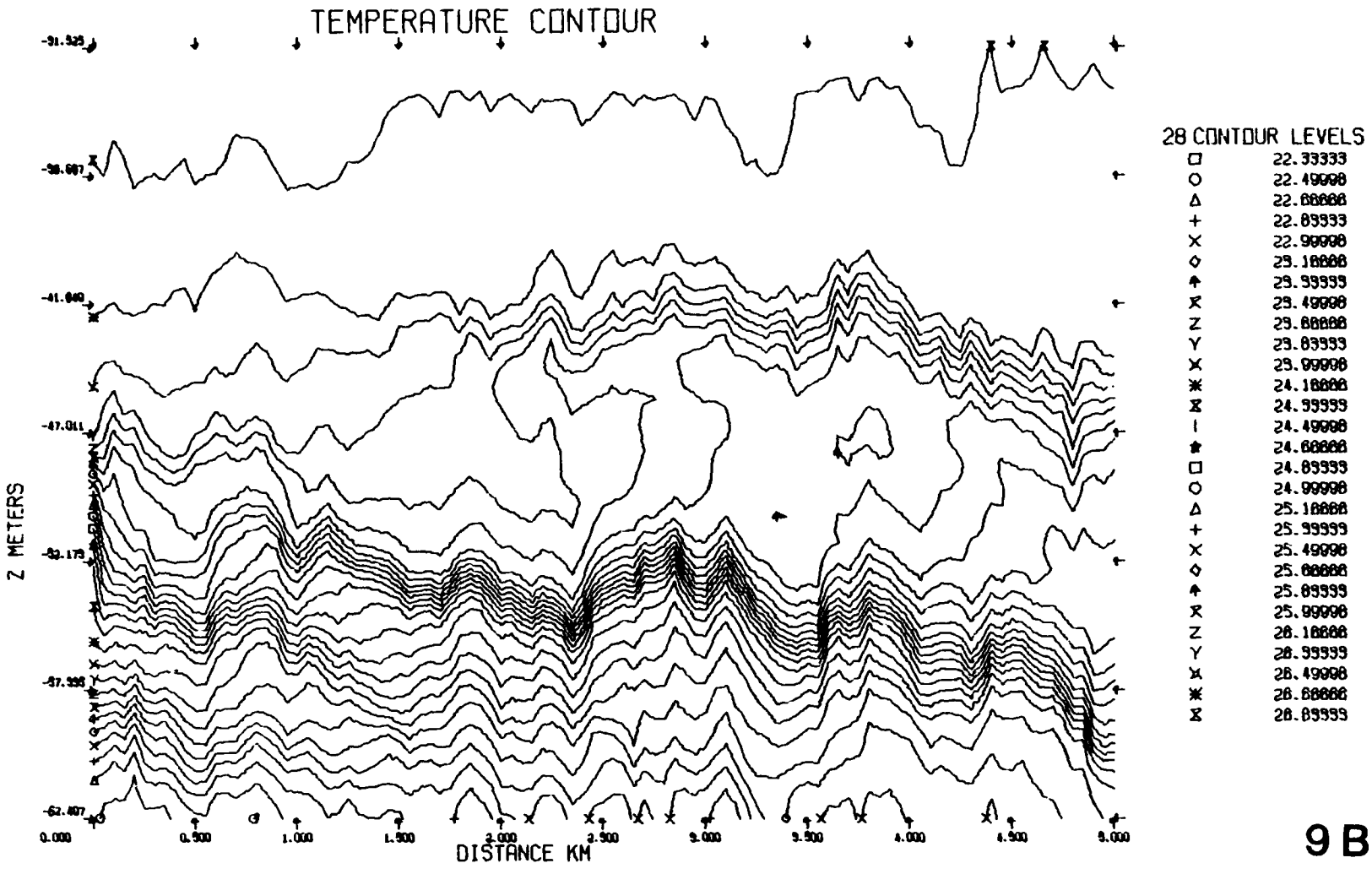
9A

RESIDUE HISTOGRAM

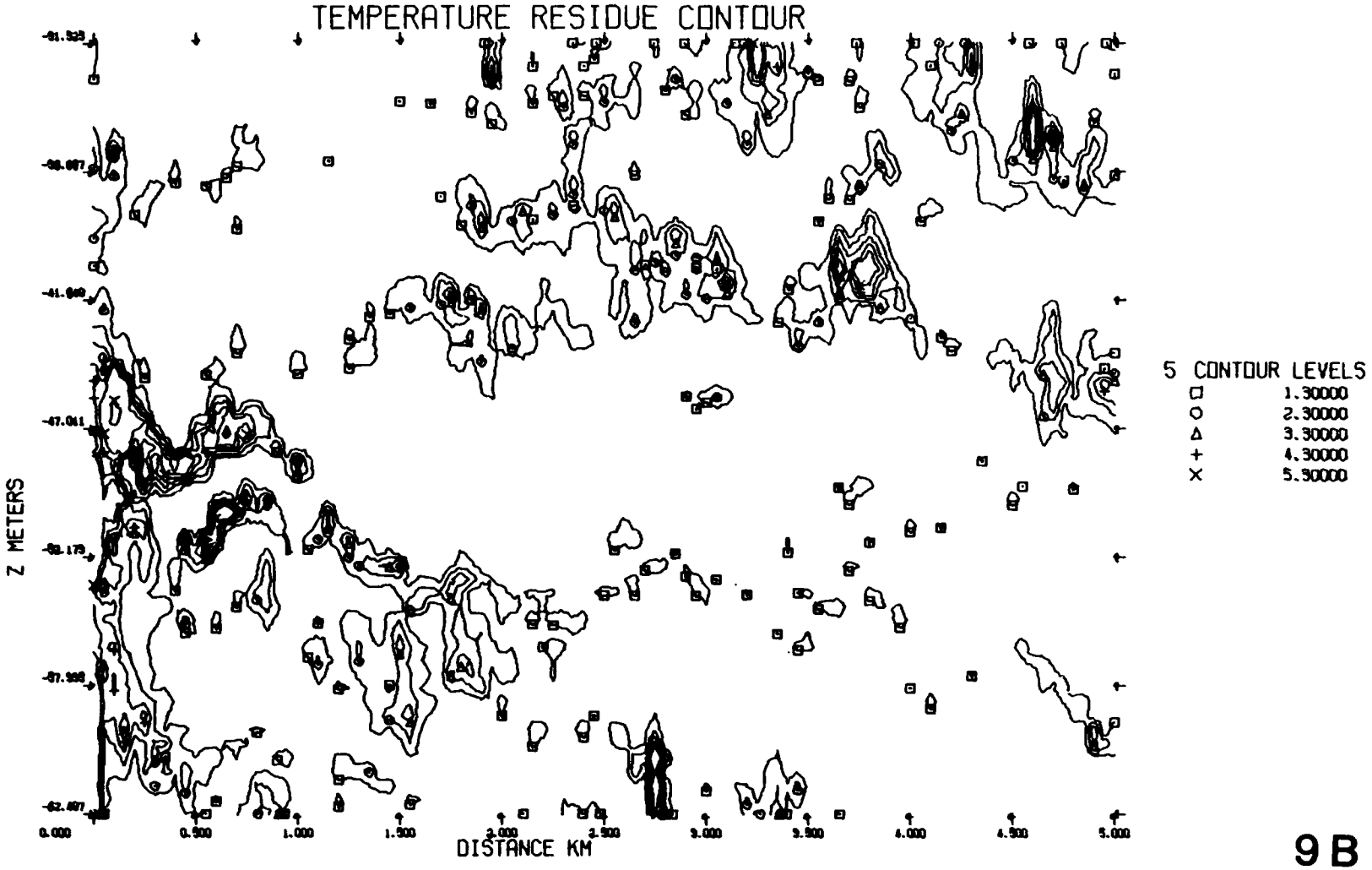


9 A


X VS Z DEVIATION
Z DEVIATION
X DEVIATION
THRESHOLD LEVEL = 1.30


TEMPERATURE CONTOUR
Z METERS
DISTANCE KM
0.000
0.500
1.000
1.500
2.000
2.500
3.000
3.500
4.000
4.500
5.000
28 CONTOUR LEVELS
22.33333
22.49998
22.66666
22.83333
22.99998
23.16666
23.33333
23.49998
23.66666
23.83333
23.99998
24.16666
24.33333
24.49998
24.66666
24.83333
24.99998
25.16666
25.33333
25.49998
25.66666
25.83333
25.99998
26.16666
26.33333
26.49998
26.66666
26.83333

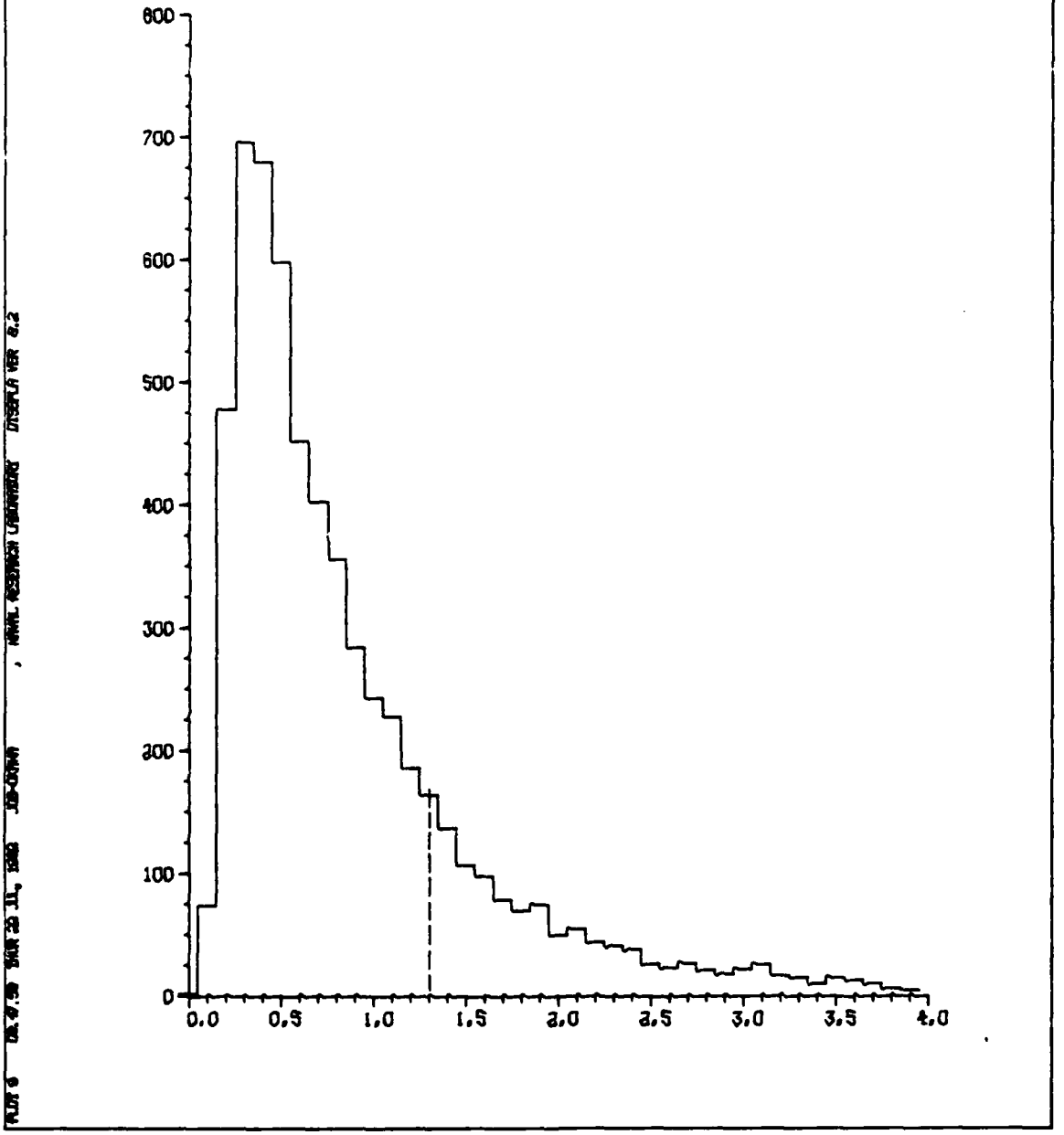
9B


TEMPERATURE RESIDUE CONTOUR
Z METERS
-61.525
-55.007
-41.969
-47.041
-52.179
-57.398
-62.407
0.000
0.500
1.000
1.500
2.000
2.500
3.000
3.500
4.000
4.500
5.000
DISTANCE KM
5 CONTOUR LEVELS
1.30000
2.30000
3.30000
4.30000
5.30000

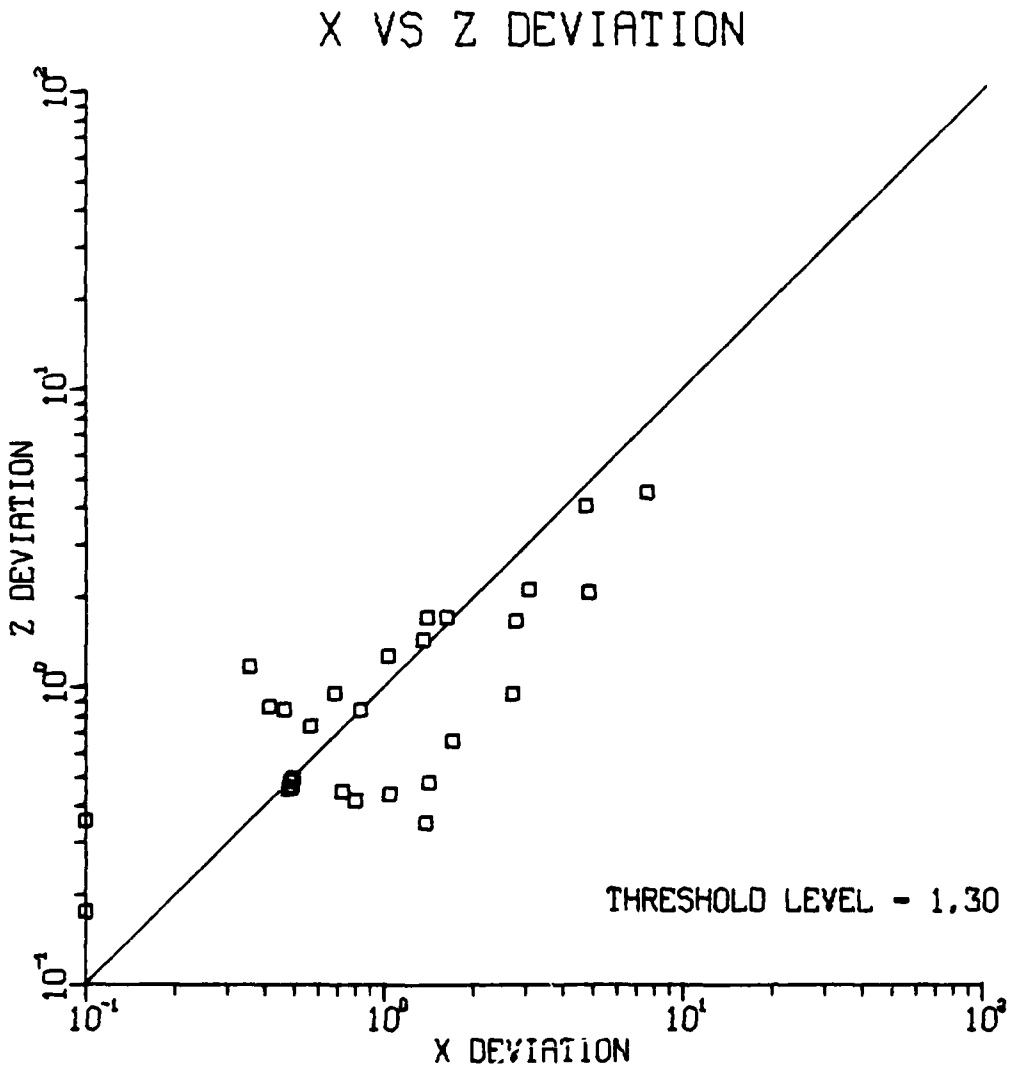
9B

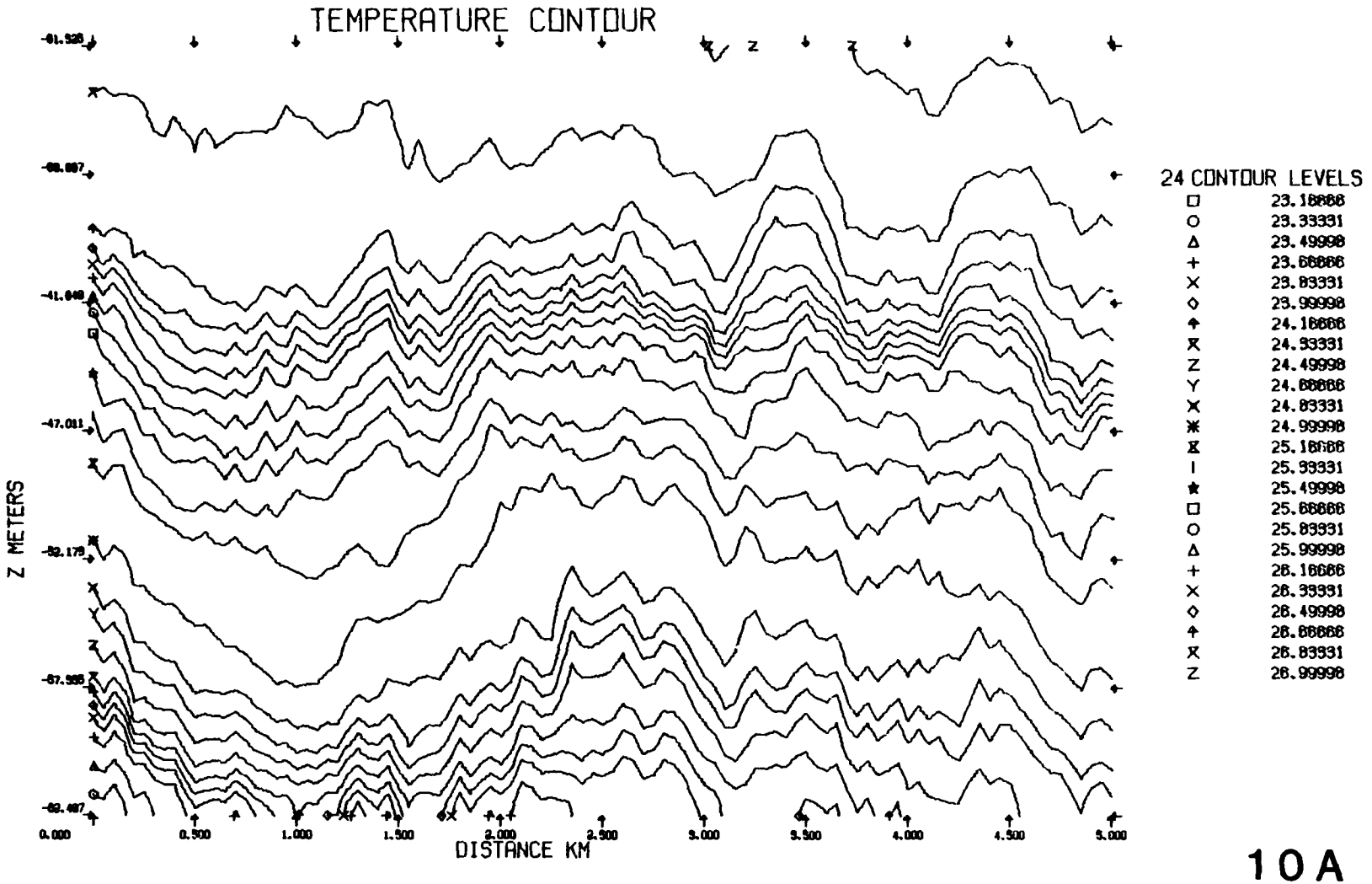
9B

RESIDUE HISTOGRAM

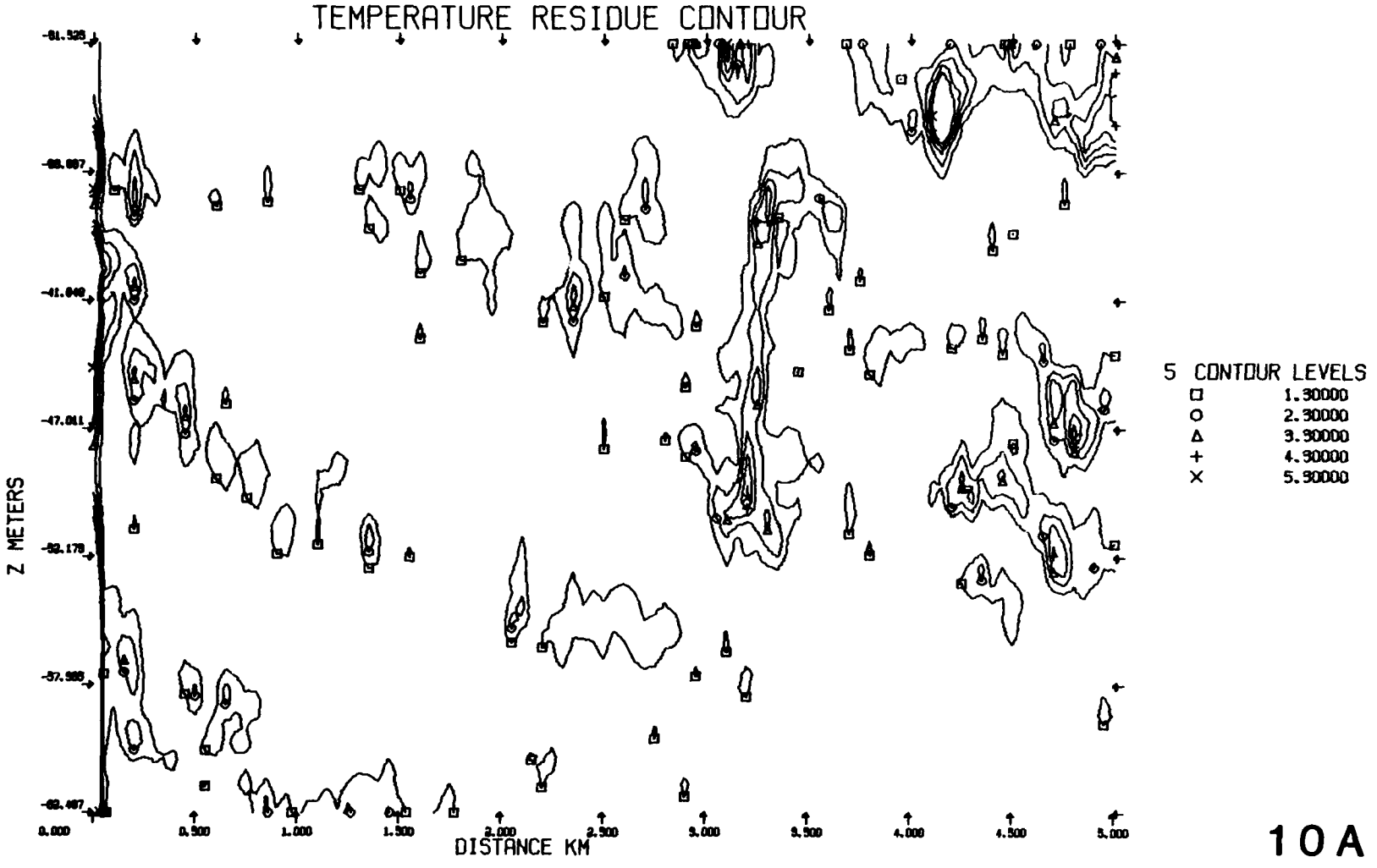


9B


X VS Z DEVIATION
Z DEVIATION
X DEVIATION
THRESHOLD LEVEL - 1.30

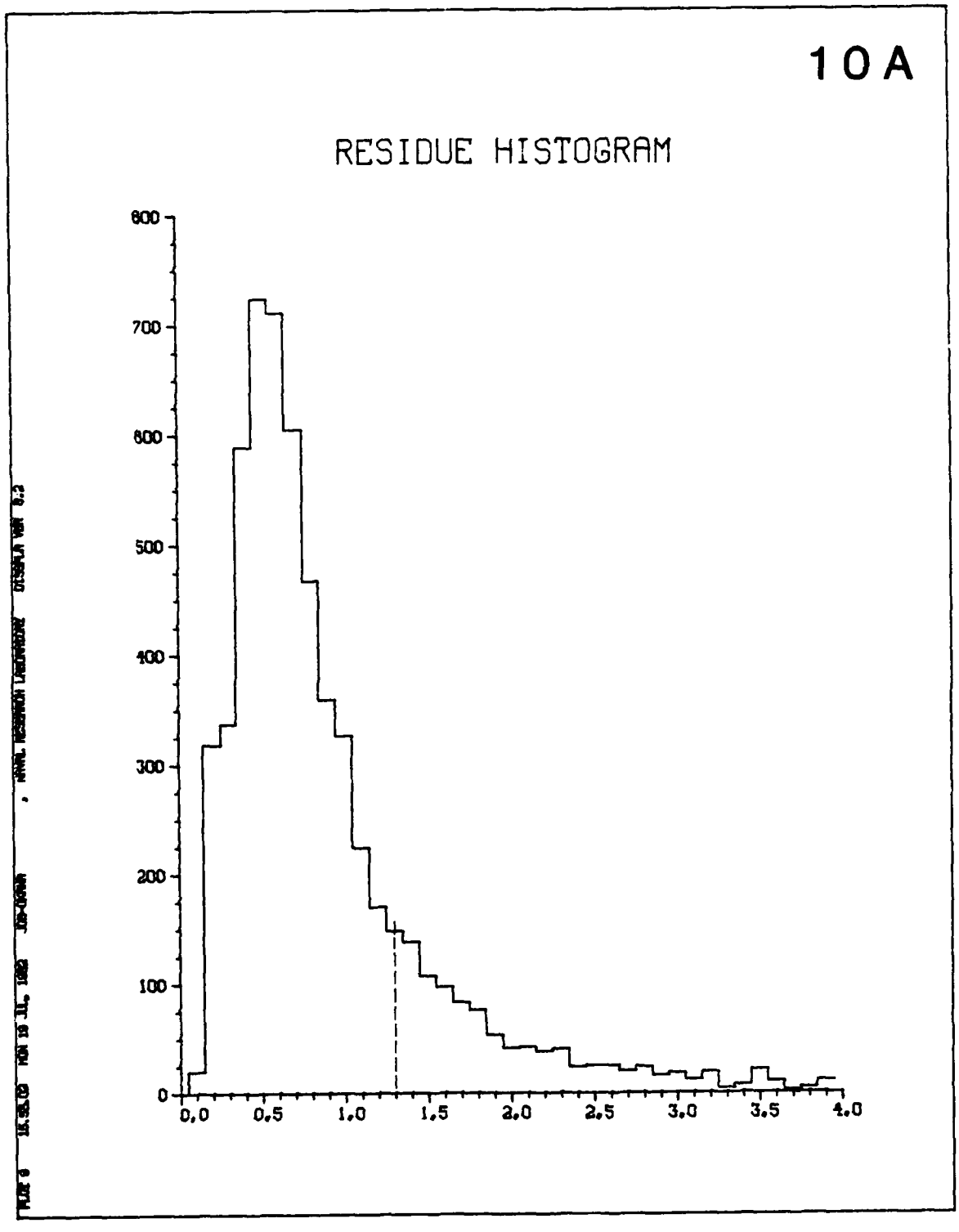

TEMPERATURE CONTOUR
Z METERS
DISTANCE KM
0.000
0.500
1.000
1.500
2.000
2.500
3.000
3.500
4.000
4.500
5.000
24 CONTOUR LEVELS
23.16666
23.33331
23.49998
23.66666
23.83331
23.99998
24.16666
24.33331
24.49998
24.66666
24.83331
24.99998
25.16666
25.33331
25.49998
25.66666
25.83331
25.99998
26.16666
26.33331
26.49998
26.66666
26.83331
26.99998

10A

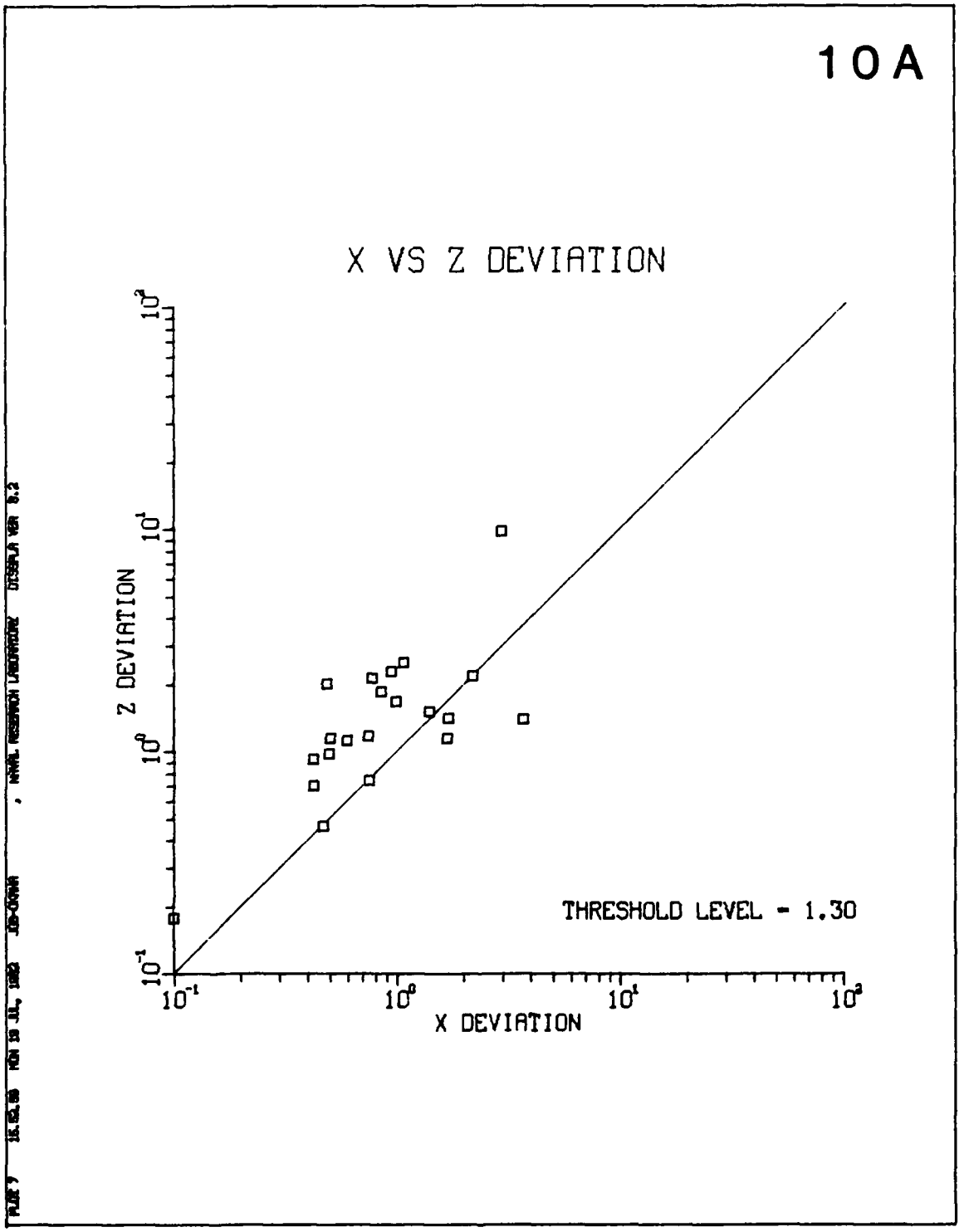

TEMPERATURE RESIDUE CONTOUR
Z METERS
-81.525
-66.667
-41.040
-47.011
-32.178
-57.986
-69.487
0.000
0.500
1.000
1.500
2.000
2.500
3.000
3.500
4.000
4.500
5.000
DISTANCE KM
5 CONTOUR LEVELS
1.30000
2.30000
3.30000
4.30000
5.30000

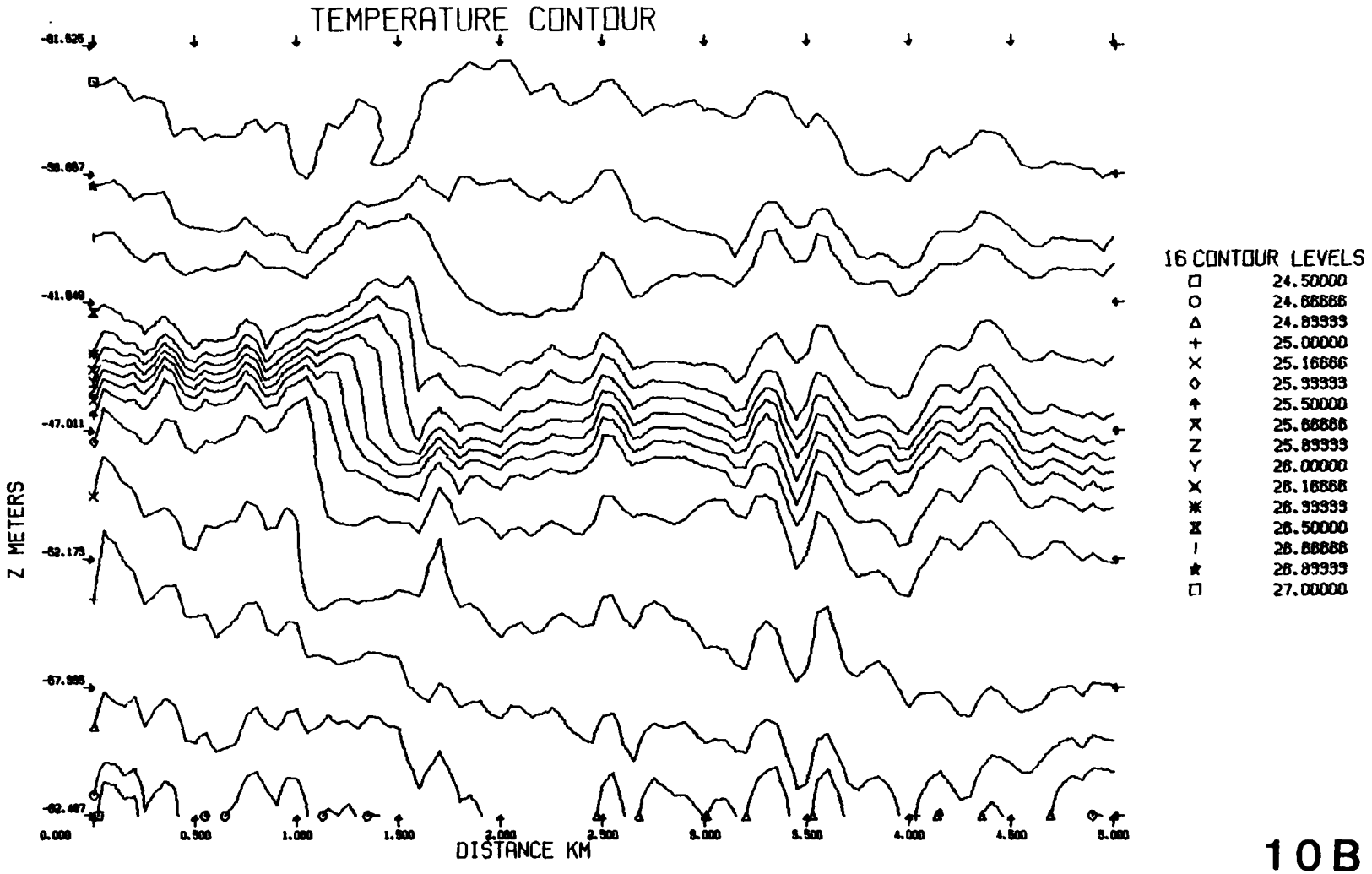
10A

10A

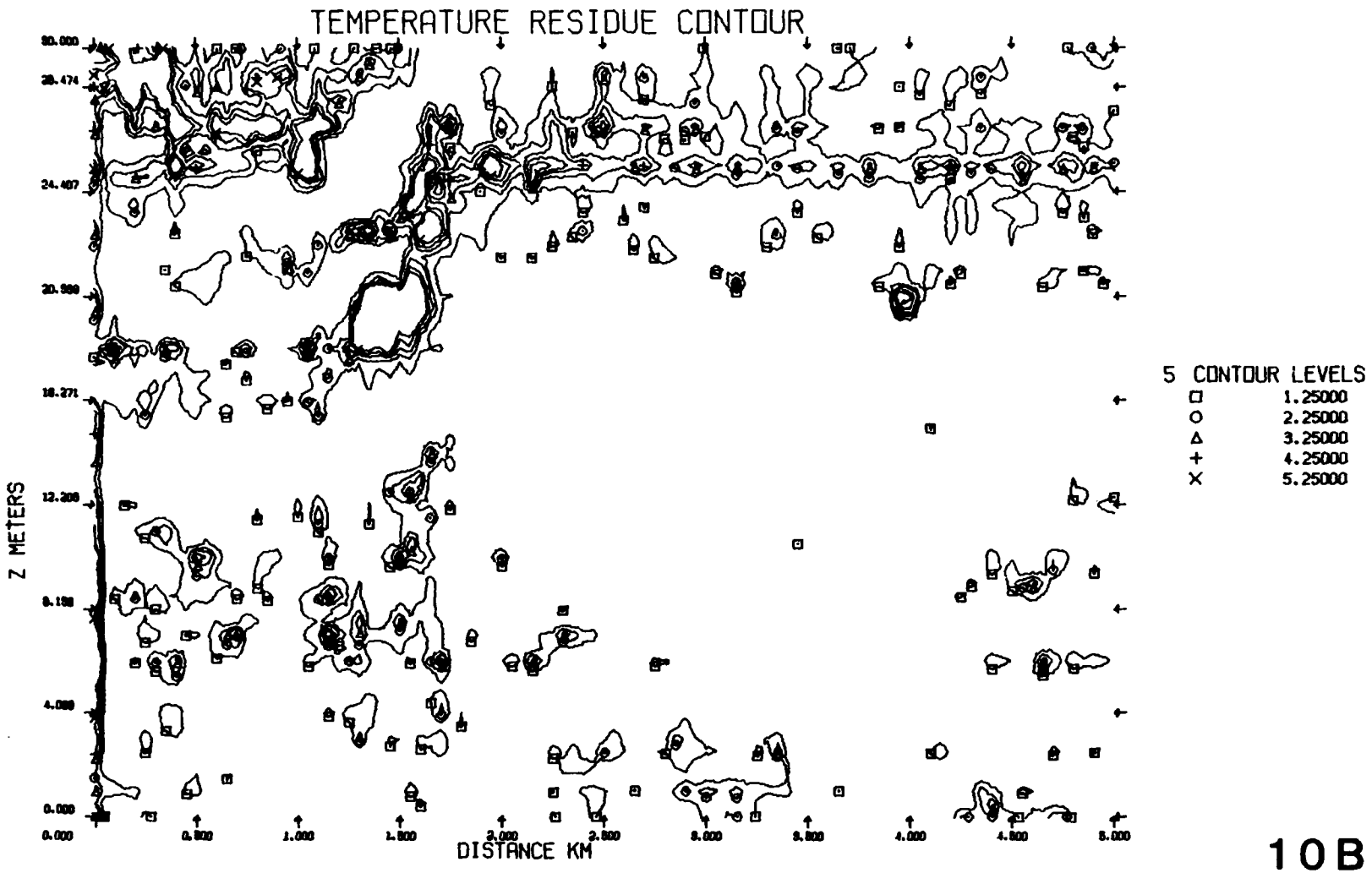

RESIDUE HISTOGRAM
800
700
600
500
400
300
200
100
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0

10A

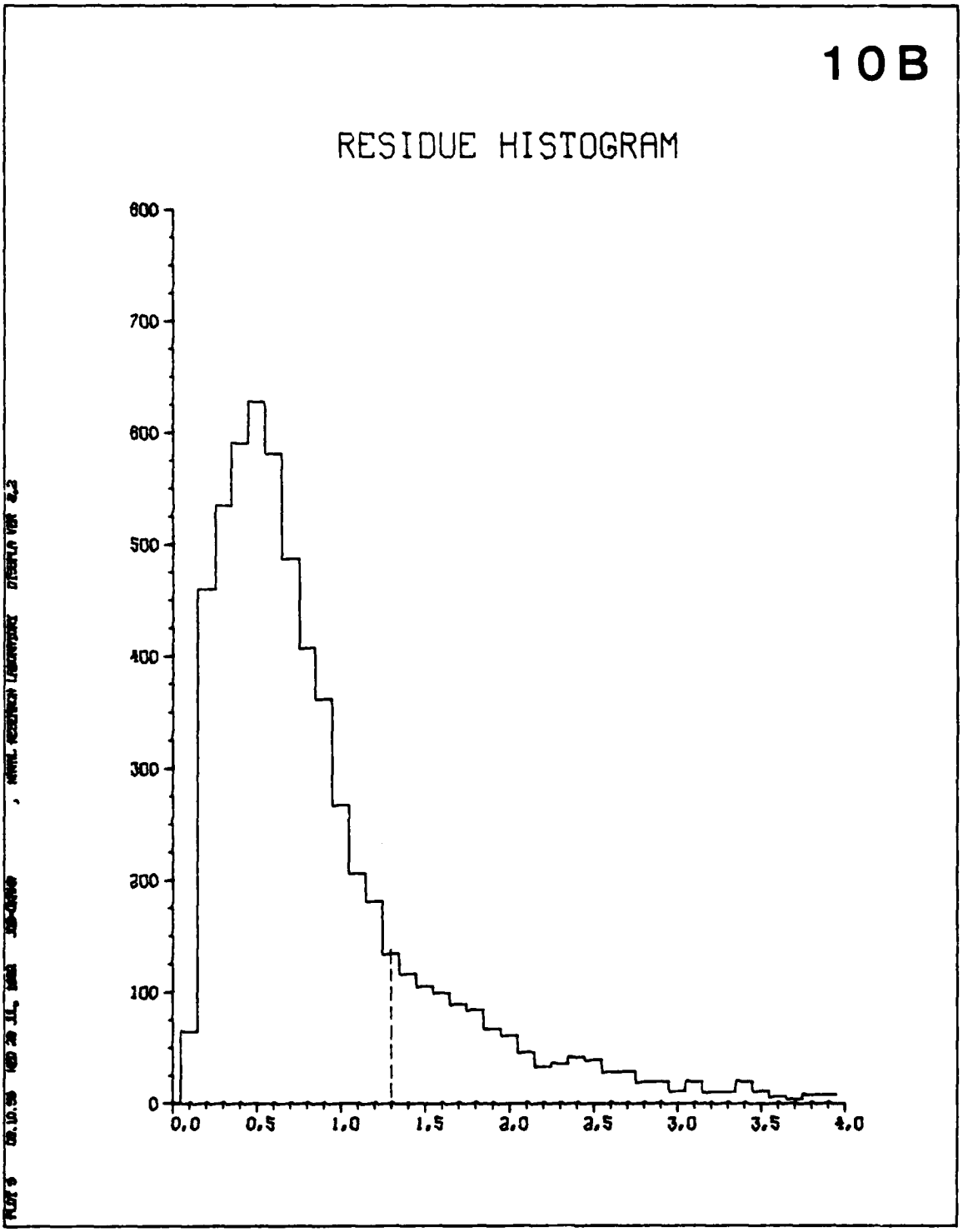

X VS Z DEVIATION
Z DEVIATION
X DEVIATION
THRESHOLD LEVEL = 1.30

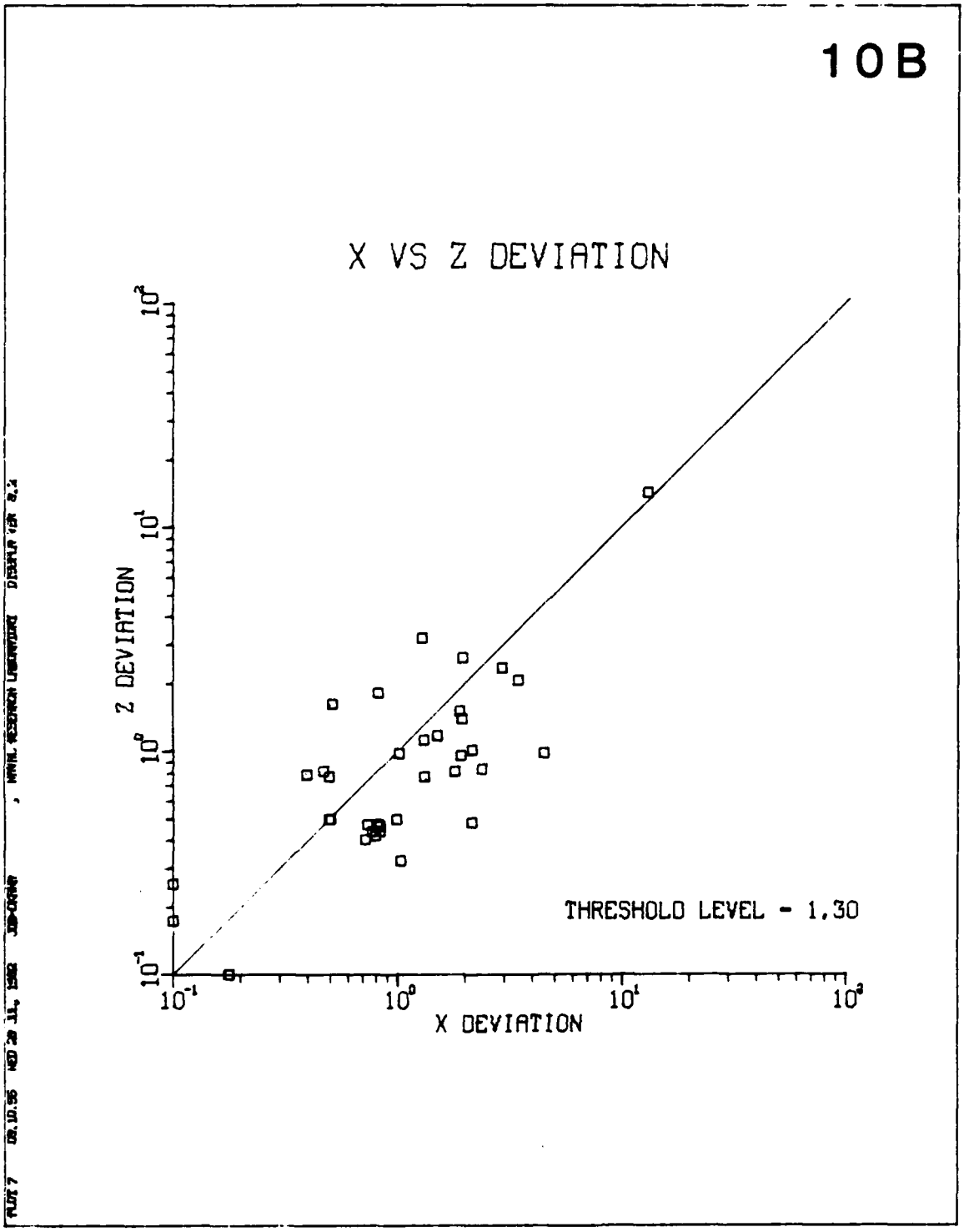

TEMPERATURE CONTOUR
-61.526
-54.687
-41.848
-47.011
-52.175
-57.338
-62.497
Z METERS
0.000
0.500
1.000
1.500
2.000
2.500
3.000
3.500
4.000
4.500
5.000
DISTANCE KM
16 CONTOUR LEVELS
24.50000
24.66666
24.83333
25.00000
25.16666
25.33333
25.50000
25.66666
25.83333
26.00000
26.16666
26.33333
26.50000
26.66666
26.83333
27.00000

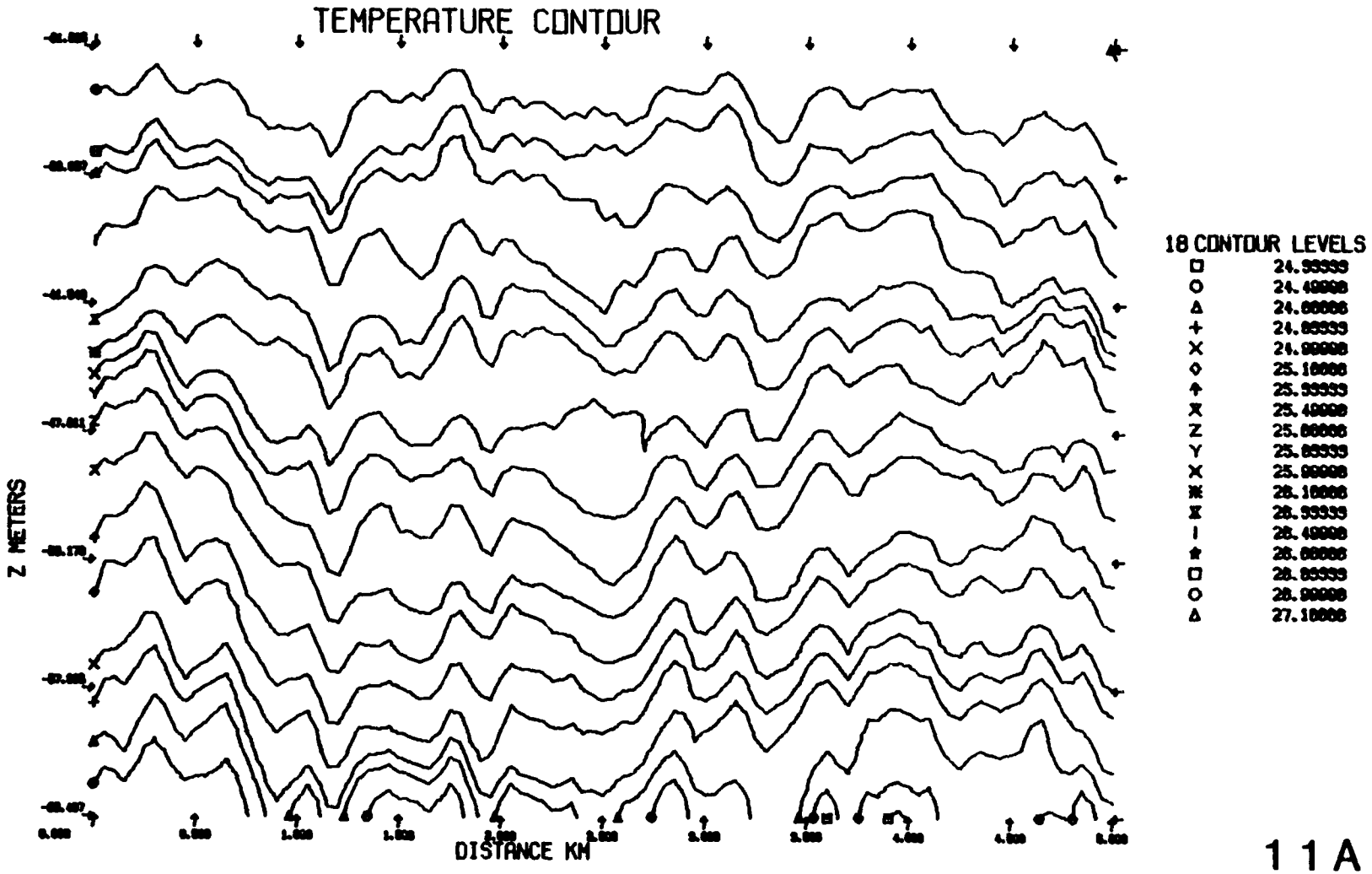
10B


TEMPERATURE RESIDUE CONTOUR
Z METERS
DISTANCE KM
5 CONTOUR LEVELS
1.25000
2.25000
3.25000
4.25000
5.25000

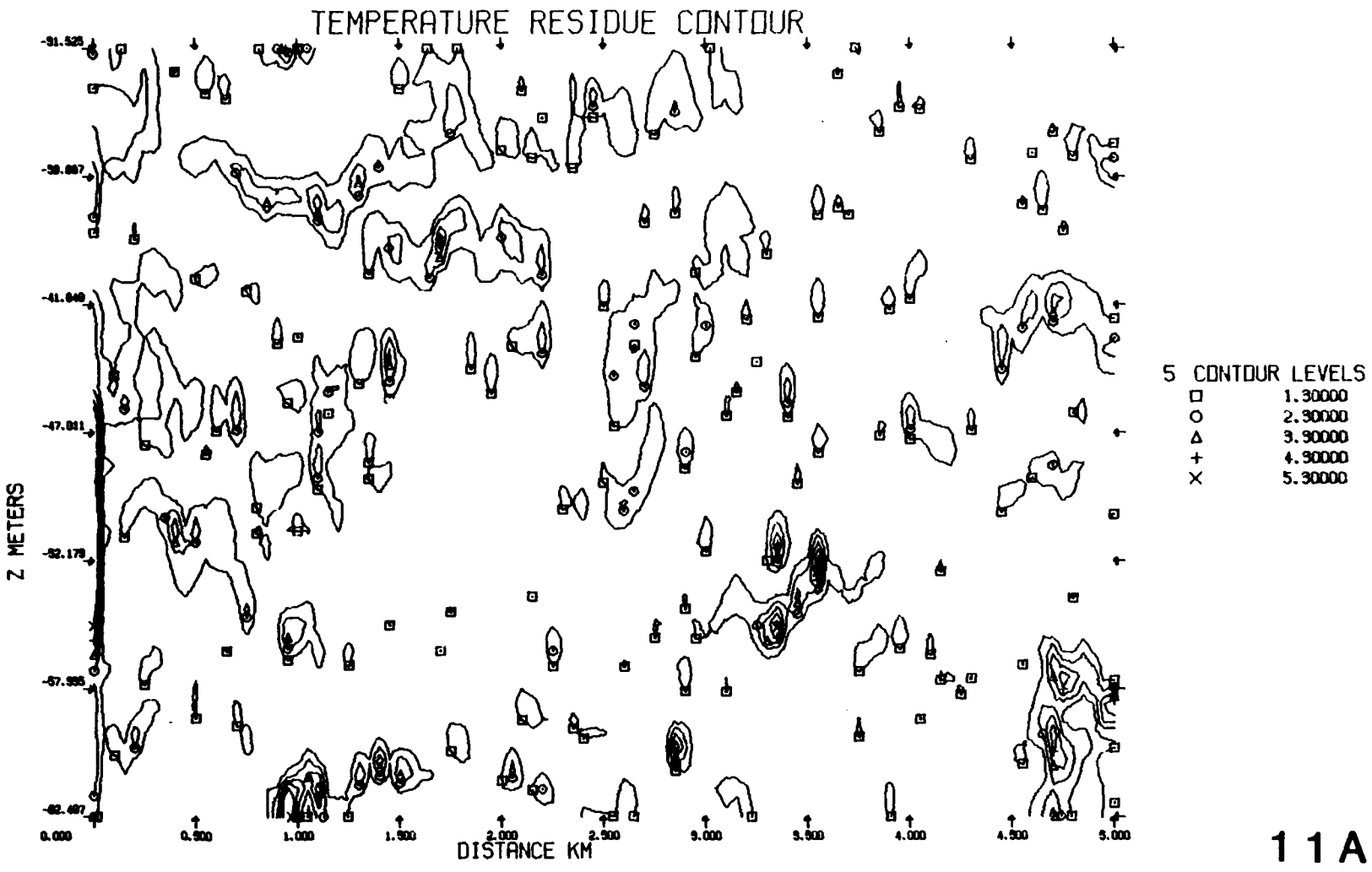
10B


10B
RESIDUE HISTOGRAM
800
700
600
500
400
300
200
100
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0


10B
X VS Z DEVIATION
Z DEVIATION
X DEVIATION
THRESHOLD LEVEL - 1.30

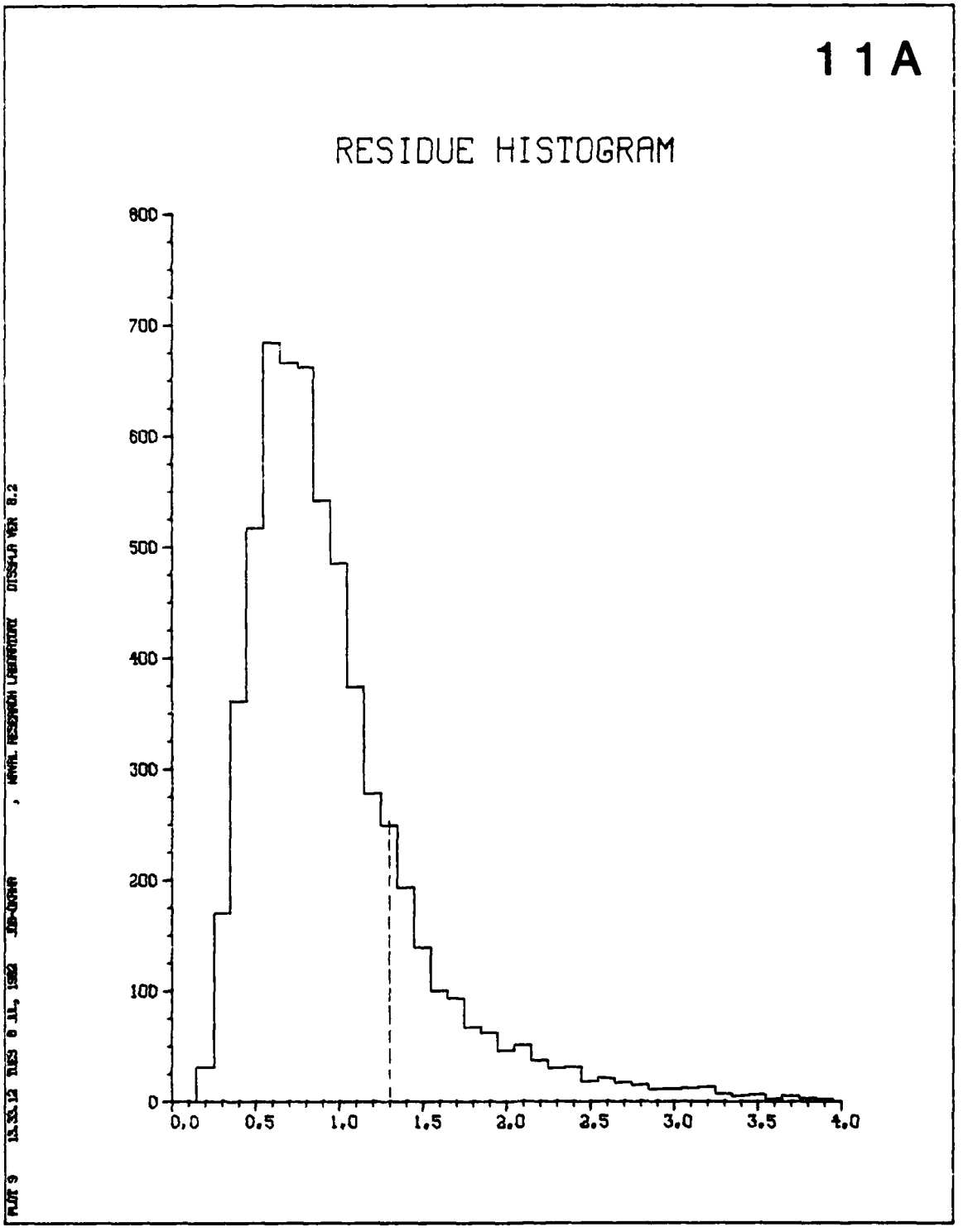

TEMPERATURE CONTOUR
Z METERS
DISTANCE KM
18 CONTOUR LEVELS
24.55555
24.49999
24.44444
24.38888
24.33333
25.16666
25.11111
25.05555
25.00000
28.16666
28.11111
28.05555
28.00000
27.94444
27.88888
27.83333
27.77777
27.16666

11A

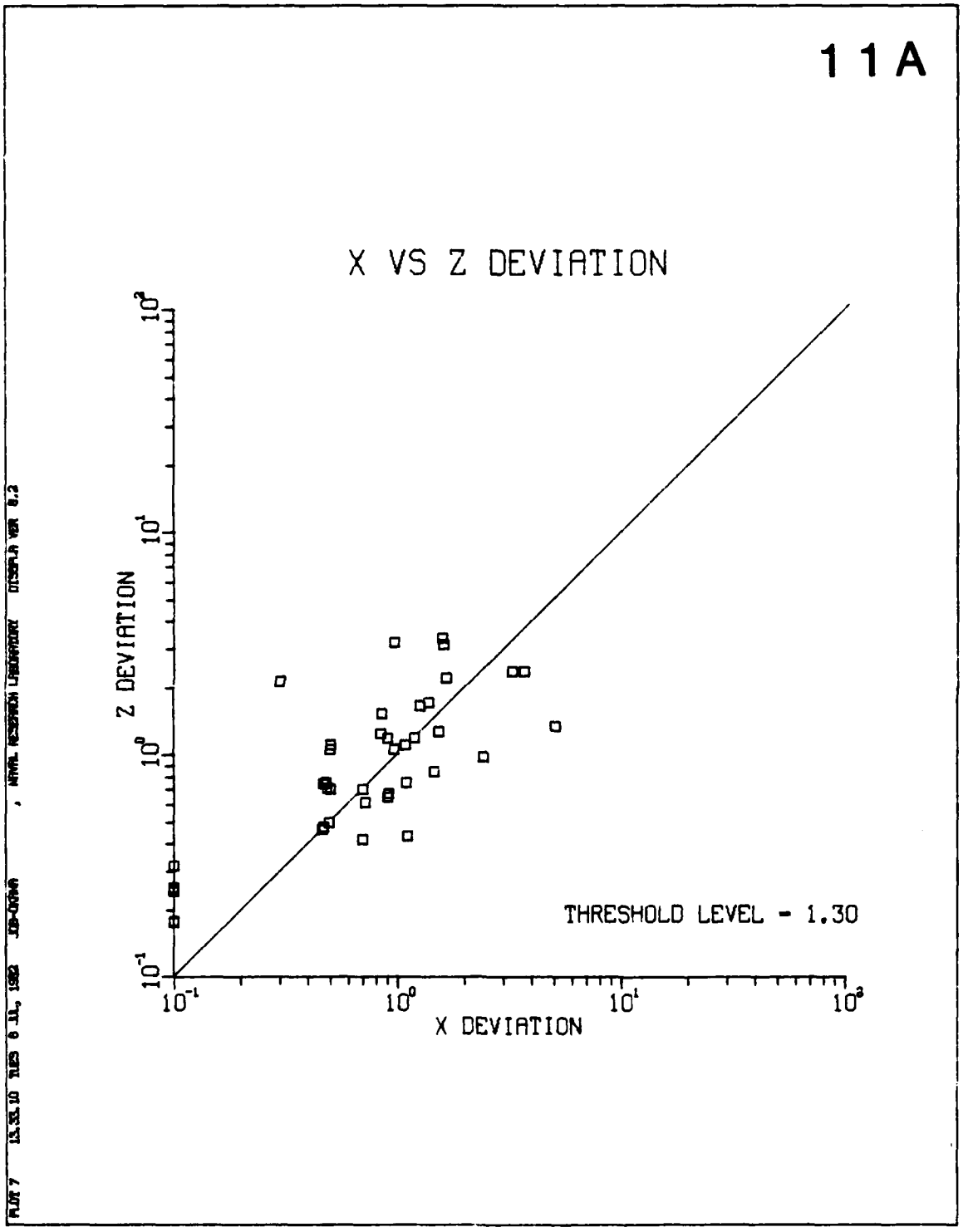

TEMPERATURE RESIDUE CONTOUR
Z METERS
-31.525
-36.887
-41.949
-47.311
-52.673
-57.935
-62.497
0.000
0.500
1.000
1.500
2.000
2.500
3.000
3.500
4.000
4.500
5.000
DISTANCE KM
5 CONTOUR LEVELS
1.30000
2.30000
3.30000
4.30000
5.30000

11A

11A


RESIDUE HISTOGRAM
800
700
600
500
400
300
200
100
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0

11A


X VS Z DEVIATION
Z DEVIATION
X DEVIATION
THRESHOLD LEVEL - 1.30

4. Conclusions.

In addition to the conclusions drawn in section 2 on the basis of the single 8A section, we conclude as follows. The rms level histograms are all quite similar, with a shape which is approximately log-normal. The patches are quite irregular in shape in general, but the simple estimates of width and height give fairly similar results for each 7 km piece of ocean. The widths range from the minimum resolvable 70 m to over 700 m, and the heights range from the minimum resolvable 50 cm to over 10 m. There is considerable scatter about a width/height aspect ratio of 150:1 (near the low side of N/f), but the widest patches often also are the highest ones.

Comparison of the isotherm plots with the patch contour plots leads to the conclusion that there possibly are several types of patches. In some cases, a patch or even a group of patches line up very regularly along isotherms. In other cases (the high patch in section 10A is an example), the patch orientation seems independent of the local trend of the isotherms.

In addition, the patch algorithm has several deficiencies which should be corrected. The preferred techniques of normalizing the rms temperature fluctuations by the local vertical temperature gradient could not be used because inaccurate relative calibrations between sensors introduced an unacceptable level of noise. Instead, the normalization was accomplished by using the mean rms fluctuation level of each sensor. This technique removed the effects of changing vertical gradients, but it was rather ad hoc and it introduced other inadequacies. In particular, it added a parameter which was the length scale over which the data were averaged. The choice here (about 7 km) was arbitrary, and detailed results would depend upon the value used. It also requires that some considerable amount of data must be handled in parallel, and it therefore could not easily be

implemented in a real time data acquisition system which would crunch the data as it came in a continuous stream.

Finally, the contour plots of the results are inefficient. They also require that a two-dimensional array of data be handled simultaneously. The patch contour plot, in particular, should be replaced by a grey-scale or, preferably, a color-coded image. This is more efficient of computer time, it can be accomplished in a one-dimensional mode as each block of data is processed, and it should yield a product which is much more pleasing to the eye.

ACKNOWLEDGMENTS

Bill Morris supervised the collection and initial processing of the temperature data. The manuscript was typed by C. Pasquini.

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